ELECTRIC MOTOR REPAIR

THIRD EDITION

Robert Rosenberg · August Hand

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Chapter 1

CAPACITOR MOTORS

MAIN PARTS OF CAPACITOR MOTORS

Capacitor-start motors are induction motors of 1/20 to 35 horsepower in size. They operate all types of loads, from small fans to large compressors. These motors have six main parts: (1) the rotating part called the *rotor;* (2) the stationary part called the *stator;* (3) the *end plates* or *brackets* (sometimes called *end bells*) bolted to the stator; (4) the *centrifugal device* located on the rotor shaft; (5) the *stationary switch* usually located on the end plate or stator shell inside the stator; and (6) one or more *capacitors* that can be located on top, on the side, or inside the motor, in the junction box, or remote of the motor. The capacitor-start motor is shown in Figure 1-1. This motor is generally operated from a single-phase lighting or power source.

According to the NEMA Standards Publications of January 1968, a capacitor motor is a single-phase induction motor with a main winding arranged for direct connection to a source of power and an auxiliary winding connected in series with a capacitor. There are three types of capacitor motors:

1. *Capacitor-start motor,* a capacitor motor in which the capacitor phase (start winding) is energized only during the starting period. This motor has switch contacts. Figure 1-2 shows a capacitor-start motor with the windings and components indicating their approximate location in the frame. Figure 1-3 is a schematic diagram. The straight-line diagram is another method to illustrate circuitry and will be explained later.
2. *Permanent-split capacitor motor,* a capacitor motor having the same value of capacitance for both starting and running conditions. Figure 1-4 is a schematic diagram of a permanent-split capacitor motor. This motor has no switch contacts.
3. *Two-value capacitor motor,* a capacitor motor using different values of effective capacitance for the starting and running conditions. Figure 1-5 is a schematic diagram of a two-value capacitor motor that has switch contacts.

The Rotor

The rotor, shown in Figure 1-6, has three elements. One is a core made up of sheets of high-grade electrical sheet steel called *laminations*. Another is a shaft

on which the laminated iron core is pressed. The third element is a squirrel-cage winding consisting of heavy cast-aluminum bars located in slots in the iron core and connected to one another by means of heavy cast-aluminum rings located on both ends of the core. In most capacitor-start motors, the rotor has a one-piece cast-aluminum winding. In older capacitor motors, copper bars and copper end rings were used. The bars must have good electrical contact with the end rings, or the motor will lose power. This condition is called *open rotor*. Silver solder should be used to restore the connections.

The Stator

The stator of a capacitor-start motor is composed of a laminated steel core with semiclosed slots, a heavy cast-iron or steel frame into which the core is pressed, and two windings of insulated copper wire that are wound into the slots and are called the *main* or *run winding* and the *start winding*. A photograph of the stator is shown in Figure 1-7, and a schematic diagram of the two windings is shown in Figure 1-8. (The start winding is connected in series with the capacitor and the stationary switch.) Both windings are connected to the power line when the motor is started; however, after the motor has reached a predetermined speed, the start winding and capacitor are automatically disconnected from the power line by means of a centrifugal device and a stationary switch.

The End Plates (End Shields or Brackets)

The end plates, illustrated in Figure 1-9, are fastened to the stator frame by means of thru bolts and serve mainly to keep the rotor in position. The bore of the end plates, in which the rotor shaft rests, is fitted with either ball bearings or sleeve bearings. These sustain the weight of the rotor, keep it precisely centered within the stator, and permit rotation without allowing the rotor to rub on the stator.

The Centrifugal Switching System

The centrifugal switching system is usually located inside the motor. Its function is to disconnect the start winding and the capacitor after the rotor has reached a predetermined speed. The usual type consists of two main parts, a stationary part (shown in Figure 1-10) and a rotating part called the centrifugal device (shown in Figure 1-11). The stationary part is usually located on the front end plate (opposite the shaft) of the motor, as in Figure 1-12, and has two contacts. It is similar in action to a single-pole, single-throw switch. Some motors have the stationary switch mounted in the stator shell. The rotating part or centrifugal device is located on the rotor, as shown in Figure 1-13.

The action of the centrifugal switching system is as follows: Figure 1-14(a) shows that when the motor is standing still or starting, the two contacts of the

stationary switch are kept closed by pressure of the rotating device's spool. At approximately 75 percent of full speed, the centrifugal device releases its pressure against the stationary switch contacts and causes them to open, thus automatically disconnecting the start winding and the capacitor from the circuit, as pictured in Figure 1-14(b).

The centrifugal device should not touch any part of the stationary switch while the motor is running, because this will cause the device to wear out. Figure 1-15 shows some other stationary switches. Many capacitor and split-phase motors now use an electronic switching device rather than a centrifugal switching system to disconnect the start winding at a predetermined speed. More information on this circuit is described in Chapter 10.

The Stator Windings

The stator windings consist of (1) a winding of insulated heavy copper wire, which is generally located at the bottom of the stator slots and is known as the run or main winding, and (2) a winding of smaller insulated copper wire, which is usually located on top of the run winding and is called the start or phase winding. These two windings are connected in parallel. When the motor is started, both the start and the run windings are connected to the line, as shown in Figure 1-14(a). Upon reaching approximately 75 percent of full speed, the stationary switch contacts open, as shown in Figure 1-14(b), and disconnect the start winding and the capacitor from the circuit, thereby causing the motor to operate only on the run winding or the main winding.

The Capacitor

A capacitor is formed when two conductors, usually aluminum, are separated by an insulator called a *dielectric*. Dielectrics are made of paper, plastic, or aluminum oxide. The conductors are usually strips of aluminum foil with terminal leads fastened to them. The foil strips and the dielectric strips are rolled together in a compact unit and placed in a sealed metal or plastic container. The container may be cylindrical, oval, or rectangular in shape and may be mounted on, in, or away from the motor. Terminals are provided to make connections. The name *capacitor* describes the device's operation, as it acts as a temporary storage unit for electrical energy; that is, it has the capacity to store electricity and provide a leading current to the motor's start winding. All capacitors have this quality, and all are electrically the same, differing only in mechanical construction.

The foil area and thickness of the dielectric determine the capacitor's microfarad, or Mfd, rating. The microfarad rating goes up as the plate or foil area is increased. A thicker foil is necessary for capacitors with a high microfarad rating because the current increases as the Mfd rating increases. The opposite is true of the dielectric: The Mfd rating goes up when the thickness of the dielectric is reduced. But the amount of current does not determine the dielectric's thickness.

The Electrolytic Capacitor

The electrolytic capacitor (Figure 1-16) is made of two strips of aluminum foil separated by layers of paper. All of this is impregnated with an electrolyte. The foil is rolled into a cartridge and placed in a container, usually plastic. Each strip of aluminum foil has a connection strip fastened to a terminal in the lid of the container. The paper is used to contain the electrolyte.

The aluminum foil is made of a high-purity aluminum that is etched or roughened to increase the surface area and thereby the capacity. The aluminum foil is subjected to a process known as *electrical forming,* which changes the foil surface from metallic aluminum to aluminum oxide.

This oxide is the capacitor's dielectric and is the only insulation between the electrode foil strips and the conductive electrolyte. The aluminum oxide conducts current in only one direction and acts as an insulator when the current flow reverses.

When alternating current (ac) is applied to the capacitor's terminals, first one oxide film and then the other become conductive. While one oxide film is conducting current, the other acts as an insulator. The entire voltage stress is applied each half-cycle across one of the oxide films. The conducting electrolyte, which acts as a common electrode or lead wire for the two foil electrodes, is a relatively high resistance conductor. The electrolyte consists of a solution of glycol, borate, and water. The water is the conductor. Current flowing through the water causes heat. Prolonged current flow (more than 3 seconds) will damage the capacitor and can make it explode.

The Oil-filled Capacitor

The oil-filled capacitor is used mainly in permanent-split capacitor motors and in two-value capacitor motors. These capacitors are designed to be connected continuously in the circuit. They are capable of constant duty and are physically much larger than are electrolytic capacitors of an equal microfarad value. They range in size from one to 70 microfarads (abbreviated μf). Figure 1-17 illustrates the oil-filled capacitor.

Oil-filled capacitors manufactured before 1980 have an environmentally dangerous oil containing polyclorinated biphenyl, or PCB. Federal legislation passed in 1978 outlawed its use. Capacitors using the safe oil are marked as such. It is advisable to avoid skin contact with the PCB oil, and it should be disposed of properly.

The plates and dielectric of all oil-filled capacitors are sealed in a metal can filled with oil. The plates and dielectric are constructed in different ways. One type uses strips of very thin aluminum foil separated by a dielectric of oil-impregnated paper. Another type uses aluminum foil separated by polypropylene film. A third type is called soggy foil, made of paper that is metallized and then impregnated with oil.

OPERATION OF SPLIT-PHASE AND CAPACITOR-START MOTORS

The most popular single-phase motors are the split-phase and the capacitor-start motors. Both motors use a variation of the two-phase motor's principle of operation. This principle involves understanding (1) the sine wave (Figure 1-18a), (2) inductive reactance, and (3) capacitive reactance.

1. The Sine Wave. Figure 1-18b shows the modified shape of the single-phase sine wave that will be used in this book. The curved line represents the magnitude and polarity of voltage. Everything above the horizontal line is positive, and that below the horizontal line is negative. The horizontal line represents the distance used in a circle containing two poles, as shown in Figure 1-19. Figure 1-20 shows a four-pole machine and the difference between electrical degrees and mechanical degrees. The horizontal line is divided into 360 electrical degrees, and each pole represents 180 electrical degrees. The sine wave represents one cycle of electricity. Both the volts and the amperes are shown in Figure 1-21. If the power source is 60 cycles per second (hertz or Hz), one cycle will take 1/60 of a second to complete. This means that the horizontal line is a measurement of time. When alternating current is generated, the generating conductor (Figure 1-22) will pass two poles in 1/60 of a second, cutting the magnetic lines of force of each pole. In Figure 1-23, the conductor at position 1 is not generating any voltage because there are no lines of force being cut at this spot. The conductor is traveling with the lines of force. Position 2 is where the most lines of force are being cut, because the conductor is traveling at right angles to the lines of force and the most voltage is generated. Position 3 is back to zero voltage at 180°. The conductor then enters the opposite pole and generates a negative voltage at maximum in position 4. Position 5 is the completion of the cycle at zero voltage and 360°. Figure 1-24 has the two poles offset and the sine wave inserted. The straight line, representing the time, is divided into degrees. Position 2 is at 90° and is 1/240 of a second later than position 1 is. Position 3 is 1/120 of a second later than is position 1 at 180°. Position 4 is 270° and 1/80 of a second later, and at position 5, the completion of the cycle is 360°, or a time lapse of 1/60 of a second.

2. Inductive Reactance. The effect of inductive reactance on a circuit is to cause the current to reach its full value after the voltage has reached its full value (Figure 1-28). The inductive reactance occurs in a coil of wire only when there is a change in voltage. When current flows in a wire, a magnetic field surrounds the wire. As the current increases, the magnetic field becomes stronger. When two or more current-carrying wires are placed side by side, with the current flowing in the same direction, the magnetic field of each will join, and a stronger magnetic field will be formed, as shown in Figure 1-25.

When direct current (dc) is applied to a resistor, the current immediately reaches its peak value. But when dc is applied to a coil of wire, there is a delay before its peak value is reached. Figure 1-26 shows this delay, which is caused by establishing a magnetic field around the coil of wire. This field is a form of energy. When the voltage is shut off, the magnetic lines of force in this field collapse. When this happens, the lines of force cut the conductors of the coil, inducing a voltage into them. This voltage will briefly maintain the current, as shown in Figure 1-27.

When alternating current is applied to a coil of wire, the result is shown in Figure 1-28. Because the voltage is constantly changing with ac, the current will always lag behind the voltage. The amount of lag will depend on the amount of inductive reactance that the circuit contains. This amount of inductive reactance can be varied by (1) the number of turns in the coil, (2) placing the coil in iron, and (3) changing the frequency.

If more turns are added to a coil, the added turns will give the coil more inductive reactance. The increase in ohmic resistance of the additional wire is negligible; however, the added turns cause a substantial increase in the lag between the voltage and the current. This increase in lag or inductive reactance in the circuit will decrease the current. Inductive reactance is a form of resistance and is measured in ohms. A decrease in current will result in a weaker magnetic field.

When a current-carrying coil is placed in iron, the iron around the coil will magnetize, demagnetize, and remagnetize in the opposite direction during each cycle. This action will also cause the current to lag behind the voltage. When the coil is placed deeper in the iron or if more of the coil is surrounded by iron, there will be an increase in inductive reactance and a decrease in current. If the hertz is increased, the rate of change will increase, and the inductive reactance will increase. Direct current flowing in a coil of wire has no inductive reactance except when turned on, shut off, or there is a change in voltage. But ac is always changing, and if there are more cycles per second, the change will increase. The windings of a 25 hertz motor have more turns than do the windings of a 60 hertz motor of the same horsepower.

3. Capacitive Reactance. Capacitance has an effect on current opposite to that of inductance. The capacitor will cause the current to lead the voltage. Figure 1-29 shows the result of capacitance in the circuit. Electrolytic capacitors are made of two aluminum strips separated by a special material containing an electrolyte. Each plate is connected to a terminal with a strip of aluminum and is riveted to the lid of the case.

When dc is applied to a capacitor, the electrons leave one plate and go to the other, as shown in Figure 1-30. The electrons will continue to flow until the voltage across the capacitor plates is equal to the applied voltage. When the line voltage is reached, very little current will flow, and the capacitor will be

charged. If the capacitor is removed from the line and a resistor is placed across the terminals, it will discharge, and current will flow until there is the same amount of electrons on both plates.

When ac is applied to a capacitor, there will be a continuous current reading, caused by the changing voltage of ac. The current lead is caused by the vacuum-like effect or pulling of electrons onto one of the plates as the voltage increases. When the voltage peaks and falls toward zero, the charged plate unloads its electrons, boosting the current or pushing it ahead of the voltage. The same thing happens to the other plate during the negative half of the cycle. This push-pull action results in a leading current, as shown in Figure 1-29. If enough capacitance is in the circuit, the current can lead the voltage nearly 90°.

To summarize, the sine wave is used to picture the separation of voltage and current and the effects of inductance and capacitance. Inductive reactance is a form of resistance in ac motors that causes the current to lag behind the voltage. It is present in a coil of wire when there is a change in voltage. Inductive reactance can be varied by (1) the number of turns, (2) the depth in iron and the amount of the coil that is in iron (for example, a motor that has a small diameter and a long stator will have fewer turns per slot than will one with a large diameter and a narrow stator), and (3) the rate of change in voltage. The more cycles per second there are, the greater amount of inductive reactance a coil of wire will have.

Capacitive reactance is used in motors to cause the current to lead the voltage in the start circuit. Capacitance has the opposite effect of inductance. As the rate of change increases (Hz), the current of the circuit increases. When more capacitance is added to the start circuit, more current will flow.

Both the split-phase and the capacitor-start motor use the two-phase principle of operation. Like the two-phase motor, they have two windings spaced 90 electrical degrees apart. Two-phase power is like two single-phase generators locked together with their voltage output 90° apart, as shown in Figure 1-31. For simplicity, the illustration shows only the top half of the sine wave. The two windings of the two-phase motor have exactly the same data. Each winding is connected to one of the voltage sources and is energized 90°, or 1/240 of a second, apart. Figure 1-32a shows a two-phase stator with a bar magnet centered in it. When phase 1 is energized, the magnet (which represents the rotor) aligns itself, as shown. Phase 2 is then energized, and the magnet aligns itself, as shown in Figure 1-32b. Phase 1 is then energized with the opposite polarity, in Figure 1-32c, and the magnet will center itself as shown. Figure 1-32d completes the cycle, attracting the magnet, as shown. This process, if done fast enough, is what happens when 60 Hz, two-phase power is applied to the motor. The 90°-current separation creates a rotating magnetic field in the stator bore. This rotating magnetic field transforms a voltage into the rotor windings. The resulting current flow in the rotor windings will create poles on the rotor. These poles will react to the stator's poles, and the rotor will try to follow the stator's rotating

magnetic field. It is very important that the two windings (start and run) be placed in the stator slots exactly 90 electrical degrees apart. This spacing will match the 90° timing of the current flow, resulting in the best possible efficiency.

The Split-Phase Motor

The split-phase motor will be referred to occasionally in this chapter. It is manufactured in sizes ranging from 1/20 to 3/4 horsepower and is used on appliances and other applications for which a small inexpensive motor can be used. The components of the split-phase motor are the same as those of the capacitor-start motor except for the start winding and the fact that there is no capacitor. If one compares the windings of a capacitor-start and a split-phase motor of the same horsepower, the run or main windings will be identical. The start-winding wire size of a split-phase motor is six to seven sizes smaller than that of the run winding and has 20 to 30 percent fewer turns than does the run windings. The start winding of the capacitor-start motor has wire of the same to four sizes smaller than that of the run winding and has 15 to 25 percent fewer turns. Figure 1-33 is a split-phase motor. Figure 1-34 shows the difference by means of a diagram. Both the capacitor-start and the split-phase motors are reversed by interchanging the start leads (T_5 and T_8). If the start leads are not available, the run leads (T_1 and T_4) can be interchanged to reverse the motor.

The stationary switch disconnects the start windings of both types of motors at approximately 75 percent of full speed. Figure 1-35 shows a split-phase motor as it would look (a) starting and (b) running at full speed.

Split-Phase Motor Operation

Like the capacitor-start motor, the split-phase motor has two windings spaced 90° electrical apart in the stator. There is a start winding and a run winding. The start winding is made of fine wire, six to seven sizes smaller than that of the run winding and has 20 to 30 percent fewer turns than the run winding does. The run winding is placed in the bottom of the slots and has more turns than the start winding does. This design gives the run winding more inductive reactance or lagging current than the start winding has. The difference in the amount of lag will make the two currents about 30 to 50 degrees apart. Figure 1-36 illustrates the separation of the two currents. Both the start and the run windings are energized to start the motor, and after 70 to 80 percent of the rated speed is reached, the starting winding is switched off by the centrifugal switching system. The motor then operates on only the run winding. Like the capacitor-start motor, the start winding of the split-phase motor can be energized for only a few seconds.

The starting efficiency of the split-phase motor (ampere per pound of torque) is not very good, for two reasons. First, the ideal timing of 90° between the start and run currents is not possible without a capacitor. Second, the small wire siz

of the start winding limits the amount of current flow. More current would make a stronger magnetic field. The reason for this motor's popularity is its low manufacturing cost, but its low starting efficiency makes it impractical to be manufactured in any larger than 3/4 horsepower. Split-phase motors are used in appliances, furnaces, small pumps, or any unit that requires a small, competitively priced motor. Very few shops rewind split-phase motors because of the low replacement cost. For this reason and because of the similarity of structure to capacitor-start motors, the repair and rewind procedures of this chapter will be addressed to the capacitor-start motors.

The capacitor-start motor is basically the same as the split-phase motor, except for the start winding. The start winding of the capacitor-start motor has 15 to 25 percent fewer turns than the run winding does. The wire size is the same size to four sizes smaller than that of the run winding.

Like the split-phase motor, the capacitor-start motor has two windings spaced 90 electrical degrees apart in the stator. The run winding has a large amount of inductive reactance because it has a large number of turns that are placed in the bottom of the slot. The current of the run winding lags behind the line voltage, as illustrated in Figure 1-37. The start winding also has a large amount of inductive reactance; however, the capacitors are connected in series with it to make its current lead the run-winding current by 90°. This 90° separation of the start- and run-winding currents gives the capacitor-start motor the same type of rotating magnetic field, while starting, as the two-phase motor has. The exact 90° separation gives the capacitor-start motor the maximum starting efficiency.

When the rotor speed reaches 70 to 80 percent of rated speed, the start winding is switched off by the centrifugal switch system, and the motor continues to run on the main or run winding. The start winding and capacitors are designed to be energized for only a few seconds. Figure 1-38 shows various-sized capacitors and accessories.

PROCEDURE FOR ANALYZING MOTOR TROUBLES

When a motor fails to run properly, a definite procedure should be followed in determining the repairs necessary to put it into running condition; that is, a series of tests is made on the motor to discover the exact trouble. These tests enable the repairperson to tell quickly whether or not the motor needs minor repairs, such as new bearings, new switches, or new leads; or whether it needs rewinding. The following steps in analyzing some of the motor problems are given in their logical order:

1. Inspect the obvious problems such as cracked end plates, bent shaft, burned leads, and scorched or discolored paint on the motor case in the area of the stator core or laminations, and if the windings are visible, check for charred or damaged coils.
2. Test the motor for bearing troubles. To do this, try to move the shaft up and

down in the bearing, as in Figure 1-39. Any such movement indicates a worn bearing. Next, turn the rotor by hand to determine whether it rotates freely. A shaft that does not rotate freely indicates bearing trouble, a bent shaft, or an improperly assembled motor, as shown in Figures 1-40 and 1-41. In any case, a fuse is likely to burn out should the motor be connected to the power line.

3. The next test is to determine whether the internal wires are touching the frame, stator, or the rotor. This is called a ground test and is carried out by using a test lamp, as shown in Figure 1-42.

4. Assuming that the previous tests show no problems, the next test is to run the motor. Some kind of current limiting device should be used for this test. A test panel (a test panel diagram for which directions are found later in this chapter in Figure 1-209) works very well for this and will prevent unnecessary damage to the motor components. Connect the motor to the test panel, and apply some current. By reading the meter it can be determined whether the windings are completely shorted or whether there is some resistance to the current flow. If there is resistance, more current or full-line voltage can be applied to the windings. Most small motors will start to turn, or attempt to turn, on ten to 15 amperes. If the motor does not turn, spin the shaft to get it started. If the motor runs, check the amperes, and compare this reading with the nameplate amperes. The nameplate amperes are for a full load, and so the no-load amperes should be less. It is not uncommon for split-phase motors and small capacitor-start motors to have ampere readings higher than the loaded nameplate amperes. This is because of the low power factor. (Power factor will be explained later in this text.)

5. If the motor has an acceptable ampere reading with the full voltage applied to the run windings but will not start, the problem should be somewhere in the start circuit. The stationary switch contacts are the most common trouble spots. If a motor starts and stops many times a day, such as with a furnace or water pump, the stationary switch contacts eventually become pitted or burned. When they no longer make good electrical contact, the stationary switch should be replaced.

6. The centrifugal device on the rotor may fail to close the start contacts. Worn thrust washers could be one of the reasons for this condition. The spool of the centrifugal device must be kept in an exact position, which will keep the start contacts together uniformly as the shaft is turned. If the contacts do not stay together as the shaft is turned, there will be "dead spots" where there is no starting torque. This condition can be detected by pushing and pulling on the shaft. There should be no more than 1/64 of an inch of movement or "end play." Pull the shaft away from the end of the motor where the stationary switch is located; apply a small amount of current from the test panel; and let the shaft turn slowly. The shaft will turn by itself only when the contacts are closed.

Thrust washers will wear out prematurely if the V-belt load is not properly aligned. This problem should be corrected when the motor is reinstalled. Thrust washers keep the rotor aligned with the stator, and the laminations of each must be in alignment. Unless the rotor or stator have shifted out of position, the centrifugal switch system should be adjusted to work with the laminations in

alignment. Improper alignment of the laminations will result in an increase in running amperes and a loss of power.

7. Replacement of the centrifugal device may become necessary if the spool or components become worn. Most devices press on the shaft. Before the old device is removed, carefully measure the spool location. Press the new device onto exactly this same spot. A thin-walled piece of pipe works well for this purpose. Care must be taken to keep the device square with the shaft. Oil should never be used on centrifugal devices.

8. Check all lead wires and terminal bolts for signs of charring. Charring is a sign of a poor electrical connection and will result in an open circuit.

An open circuit may develop within a winding. The most common place for an open to occur in a winding is in the coil-group connections. If an open cannot be easily located, the motor should be rewound.

Detailed tests for capacitors are found on page 54 of this chapter.

REWINDING THE CAPACITOR-START MOTOR

After previous tests have shown that the motor's windings are burned out or severely shorted, rewinding is required in order to recondition it. Before the motor is taken apart, the end plates and frame are marked with a chisel so that it may be reassembled properly. One chisel mark is made on the front end plate and the adjacent frame, and two marks are made on the back end plate and also at a corresponding point on the frame, as shown in Figure 1-43. The motor is then disassembled and made ready for repair.

The most common type of capacitor-start motor has two windings on the stator, a run winding and a start winding. The run winding is always placed at the bottom of the slots. The start winding is placed above this in the slots but is displaced 90 electrical degrees; in other words, the start poles are placed midway between the run-winding poles. An examination of the start winding of a capacitor-start motor will reveal that it is usually wound with wire of slightly smaller size than that of the main winding.

Rewinding a capacitor motor having a damaged winding consists of a number of separate operations: (1) taking data, (2) stripping the windings, (3) insulating the slots, (4) rewinding, (5) connecting the winding, (6) testing, and (7) baking and varnishing.

Taking Data

Taking data is one of the most important of the above operations. It consists of noting certain specific information concerning the old winding, so that no difficulty will be encountered when the motor is rewound. The information is recorded before and during the process of stripping the stator core of its windings. The best procedure is to obtain as many data as possible before the stripping operation. The information that should be obtained for both the run and start windings includes (1) nameplate data, (2) the number of poles, (3) the pitch of the coil (the number of slots that each coil spans), (4) the number of turns in each

coil, (5) the size of the wire on each winding, (6) the kind of connection (number of circuits), (7) the position of each winding, and (8) the number of slots.

The information listed above must be recorded in such manner as to enable any motor repairperson to rewind the motor without loss of time because of inadequate data regarding the original winding. To explain the proper manner of obtaining the desired information, it will be assumed that a 32-slot, four-pole motor requires rewinding. The well-trained repairperson would proceed as follows to gather the necessary data.

Record the nameplate data on a data sheet such as shown on page 13. The information contained on the nameplate is very important, as it tells at a glance the make of the motor, the horsepower, the voltage on which it must be operated, and the speed at full load. And among other things, it indicates whether it is an ac or dc motor, the current it draws at full load, the type, and its serial number.

The minimum amount of information on a nameplate of a single-phase motor should be (1) manufacturer's type and frame designation, (2) horsepower output, (3) time rating, (4) temperature, (5) rpm at full load, (6) frequency, cycles per second (hertz), (7) number of phases, (8) voltage, (9) full-load amperes, (10) code, (11) design letter for integral-horsepower motors, (12) for motors equipped with thermal protection the words *thermally protected,* and for motors rated more than 1 hp a type number, and (13) service factor.

Figure 1-44 shows a 32-slot, four-pole stator of a capacitor-start motor as it would look if viewed from one end. Each winding consists of four sections, known as *poles* or *pole groups*. To determine the number of poles in the motor, count the number of sections in the run winding. In Figure 1-44 the four sections of the run winding indicate a four-pole motor. If there were six sections in the run winding, it would indicate a six-pole motor. The number of poles in an induction motor governs the speed of the motor, and it is therefore essential that the correct number be recorded. A two-pole motor will rotate just below 3,600 rpm; a four-pole motor about 1,750 rpm; a six-pole motor just under 1,200 rpm; and an eight-pole motor slightly under 900 rpm. These speeds apply only when the motor is supplied with 60-cycle alternating current; different speeds will prevail for other frequencies.

Should the winding assembly be cut at one point and rolled flat, the winding would appear as in Figure 1-45. Notice the location of the run winding with respect to the start winding. The start winding overlaps two poles of the run winding. This is always true in capacitor-start and split-phase motors, regardless of the number of poles or the number of slots in the motor. *Recording the location of the run winding with respect to the start winding is highly important.* If they are placed in a different location in rewinding, the motor may not start properly. Actually, the run and start windings are separated by 90 electrical degrees. This is true no matter how many poles the motor has. However, the number of mechanical degrees between windings will differ with the number of poles in the motor. In the four-pole motor the windings are 45 mechanical degrees apart, and in a six-pole motor they are 30 mechanical degrees apart.

The center of a pole is exactly 90 electrical degrees from the side of the coil

group. This is the area between the coil sides that have their currents flowing in opposite directions from each other. There should be at least two teeth (one empty slot) between the two sides. Figure 1-46 shows two empty slots and three teeth in the center. The center of the run-winding pole determines where the start winding is to be placed. In Figure 1-46, the center is on a tooth. The start-winding groups start to the left and to the right of this tooth. The center of the start winding must be 90 electrical degrees from the center of the run winding.

If a pole of either the run or the start winding of the motor is examined closely, it will be found to consist of three separate coils that have been wound one at a time, as illustrated in Figure 1-47. Also, each coil is wound in two slots that are separated by one or more other slots. The number of slots separating the sides of a coil, including the slots in which the winding lies, is called the *pitch* or *span* of a coil and is recorded as "1 and 4" or "1 and 6" or "1 and 8," as the case may be. This is shown in Figure 1-48. These coils protrude a certain distance from the ends of the slots. This is called the *end room*. This distance should be measured and recorded. It is important that the new coils do not extend beyond the slots any farther than this distance; otherwise the end plates may press against the coils and cause a ground.

The next step is to record the information thus far obtained regarding the positions of the windings and the pitch of the coils. It may be recorded by showing all the slots and the windings, as illustrated in Figure 1-49, which shows a motor with 32 slots. In this method, the spans of all the coils are recorded merely by drawing curved lines in the proper slots. This is recorded first for the start winding because it is on top and more visible than is the run winding. The pitch of the run-winding coils can be seen more easily if the ends of the start winding are lifted. Each of the curved lines represents one coil of a pole. A complete data sheet for listing the information to be taken follows:

DATA SHEET FOR CAPACITOR ST. AND SPLIT PHASE MOTORS.

Make

H.P.	R.P.M	Volts	Amps
Cycle	Type	Frame	S.F.
Temp. Rise	Model	Serial #	Phase
No. of Poles	Code	No. of Slots	Time Rating

Winding	Size Wire	No. of Circuits	Pitch	Turns
Run				
Start				

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	1
Run																																					
Start																																					

Rotation CW	CCW	Voltage Conn.
Bore	Length	Cap. Size
Coil Extention	Front	Back

Not all motors have 32 slots. Most capacitor-start motors have 36 slots; some have 24. A recording for a 36-slot, four-pole motor is shown in Figure 1-50 and one for a 24-slot, four-pole motor in Figure 1-51. Note in Figure 1-51 that the outer coils of each pole in this motor overlap one another and are placed in the same slot. This condition exists in many motors. Note also in Figure 1-50 that the poles of the start winding have three and four coils in adjacent poles.

Another item of the data that should be recorded is the location of the run-winding poles with respect to the frame itself. In some motors the center of each main pole is identified by a change in slot size. This is sufficient for properly locating the pole in rewinding. However, in the absence of the odd-sized slot, the best position for the pole is to locate it exactly between the thru-bolt holes.

The type of connection is the next item to be recorded. This can be obtained only if one is familiar with methods of winding and connecting the poles to one another. Capacitor-start motors are connected in a variety of ways, such as single voltage, dual voltage, externally reversible, and two speed. In order to be able to record the kind of connection in the motor, the repairperson must know the various connections to be found in this type of motor. It is best, therefore, to read and study the sections "How to Recognize a Connection" and "Connecting Procedure" before attempting to record the connection.

Information regarding the number of turns of wire in each coil must be obtained and recorded. This is done by counting the turns as they are unwound or by cutting the coils on one end and counting the ends. It is important to note also whether or not there is more than one strand per conductor. Sometimes two or more strands of a smaller wire are used instead of one strand of a larger size. When this is done, it is called wires in hand or wires in parallel. When two or more wires are used in place of one larger wire, the number of strands counted in each coil must be divided by that number to get the number of actual turns in the coil. For example, if 27 strands are counted in a coil with one strand of wire, there would be 27 turns. If 3 strands are used, there would be 27/3 or 9 turns. The size of the wire, as determined by a wire gauge or micrometer and chart, must also be recorded. These data are noted as the windings are removed from the stator.

If the stator is to be rewound, it is very difficult and time-consuming to remove the windings from the core without first softening or charring the varnish and insulation. The windings are extremely hard because of the varnish, and to attempt to remove the wires before charring requires considerable time. The procedure in many shops is to place the stator in a burn-off oven for several hours at approximately 600° to 700° F and then permit it to cool off. The burn-off oven may be gas fired or electric. It is important that the heating be controlled to prevent warping of the frames and damage to the lamination plating. Usually the coils on the back side of the stator are cut off flush with an air chisel or electric chisel before being placed in the oven (Figure 1-52). Removing the rest of the

coils after charring is relatively simple because the remaining coils may be pushed through the slots from the other side of the winding.

It is important to remember that the old windings should not ignite, that the temperature does not increase too rapidly, and that the stator should be allowed to cool off gradually. This applies to all types of motors. Too much heat can destroy the coating between the laminations and will cause hot spots in the core. Chemicals can be used to soften the windings for stripping, or they can be heated to 350° in an oven and pulled out while they are still soft.

During the process of stripping, the number of turns in each of the coils of one or two poles of the start and run windings must be counted. This information is then recorded on the data sheet beside the curved lines that represent the pitch of the coils. At this time, also, the size of the wire of both the run and the start windings is measured, usually by means of an American Wire Gauge or micrometer after it is stripped clean of its insulation. The coating must be burned from the wire before measuring. Scraping the wire could change its diameter. It is then recorded on the data sheet. There is a wire-size chart in the Appendix section.

TERMINAL MARKINGS FOR SINGLE-PHASE MOTORS

The following standards for terminal markings have been reproduced from the National Electrical Manufacturers Association Standards Publication.

A. Dual Voltage

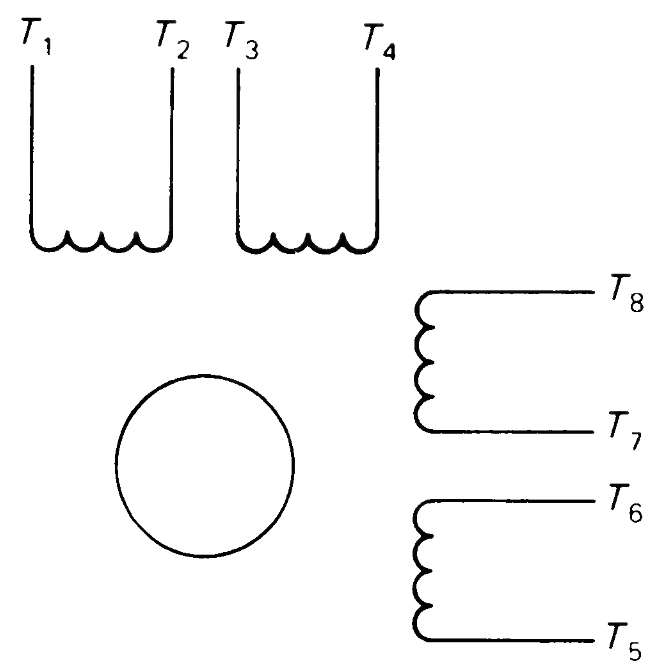
Regardless of type, when a single-phase motor is reconnectible in series-parallel for dual voltage, the terminal marking is determined as follows:

To assign terminal markings, the main winding is assumed to be divided into two halves, and T_1 and T_2 should be assigned to one half and T_3 and T_4 to the other half.

To assign terminal markings, the auxiliary winding (if present) is assumed to be divided into two halves, and T_5 and T_6 should be assigned to one half and T_7 and T_8 to the other half.

Polarities shall be established so that standard direction of rotation (counterclockwise facing the end opposite drive) is obtained when the main winding terminal T_4 and the auxiliary winding terminal T_5 are joined or when an equivalent circuit connection is made between the main and auxiliary winding.

The terminal marking arrangement is shown diagrammatically in the following figure:



Dual Voltage

NOTE 1—It has been found to be impractical to follow this standard for the terminal markings of some definite-purpose motors.

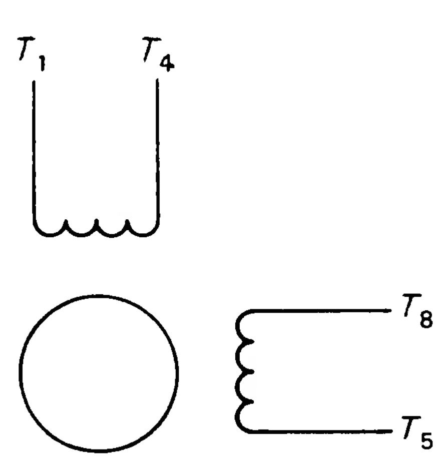
NOTE 2—No general standards have been developed for terminal markings of multispeed motors because of the great variety of methods employed to obtain multiple speeds.

B. Single Voltage

If a single-phase motor is single voltage or if either winding is intended for only one voltage, the terminal marking is determined as follows:

T_1 and T_4 is assigned to the main winding and T_5 and T_8 to the auxiliary winding (if present), with the polarity arrangement such that standard direction of rotation is obtained if T_4 and T_5 are joined to one line and T_1 and T_8 to the other.

The terminal marking arrangement is shown diagrammatically in the following figure:



Single Voltage

Terminal Markings Identified by Color

When single-phase motors use lead colors instead of letter and number markings to identify the leads, the color assignment is determined from the following:

T_1—Blue	T_5—Black
T_2—White	T_8—Red
T_3—Orange	P_1—No color assigned
T_4—Yellow	P_2—Brown

SCHEMATIC DIAGRAMS OF CAPACITOR-START MOTORS

The schematic diagrams in Figures 1-121a, b, c, d, and e are reproduced through the courtesy of NEMA and show the terminal markings of single- and dual-voltage capacitor-start motors with and without a thermal protector. These diagrams are part of the NEMA Standards Publication. Data on terminal connections are found in Chapter 1, page 15.

Auxiliary Devices Within Motor

The presence of an auxiliary device or devices such as a capacitor, starting switch, thermal protector, and so on, permanently connected in series between the motor terminal and the part of the winding to which it ultimately connects should not affect the marking unless a terminal is provided at the junction.

When a terminal is provided at the junction, the terminal marking of this junction is determined by the part of the winding to which it is connected. Any other terminals connected to this auxiliary device are identified by a letter indicating the auxiliary device within the motor to which the terminal is connected.

Auxiliary Devices External to Motor

When the capacitors, resistors, inductors, transformers, or other auxiliary devices are housed separately from the motor, the terminal markings are those established for the device.

Marking of Rigidly Mounted Terminals

On a terminal board, the identification of rigidly mounted terminals is either by marking on the terminal board or by means of a diagram attached to the machine. When all windings are permanently connected to the rigidly mounted terminals, these terminals may be identified in accordance with the terminal markings specified in this publication. When the windings are not permanently attached to rigidly mounted terminals on a terminal board, the rigidly mounted terminals should be identified by numbers only, and the identification need not coincide with that of the terminal leads connected to the rigidly mounted terminals.

HOW TO RECOGNIZE A CONNECTION

The basics of connecting motors must be understood before connections can be recognized. Usually a group of coils connected together will represent a pole and is called a pole group. The coils may be arranged in concentric form, as in Figure

1-47, or in lap form, as in Figure 1-53. The turns in the coils and each coil of the pole group must be wound in the same direction. Each coil of the pole group will lie in different slots.

The diagrams used in the following illustrations are explained in Figure 1-54a. The left illustration shows the pole group as it looks in the slots of a stator; the center illustration shows how it would look laid flat; and the right illustration is a pole group in the form of a rectangle as it appears in diagrams. The leads or ends of the pole group are shown coming out of the right and left sides of the rectangle. The following connections are called *straight-line diagrams*. Figures 1-54b through 1-69 all are run-winding diagrams.

Figure 1-54b depicts a four-pole, one-circuit connection. A one-circuit connection means there is one electrical path or circuit through all the pole groups. One circuit is also referred to as a series connection because all the pole groups are in series with one another.

The number of circuits in a winding can be determined by the number of pole groups fastened to each terminal lead. Figure 1-55 is a two-circuit connection, having two pole groups fastened to lead T_1 and two pole groups fastened to lead T_4. Figure 1-56 is a four-circuit connection, having four pole groups fastened to leads T_1 and T_4.

The number of circuits possible in a winding will be any number that will divide evenly into the number of single-circuit (one wire in hand) pole groups. A four-pole winding that has four single-circuit pole groups can be connected in one, two, and four circuits. A six-pole winding with six single-circuit pole groups can be connected in one, two, three, and six circuits.

Pole groups are sometimes wound with two or more wires. If two wires, as illustrated in Figure 1-57, both are fastened to one lead wire, they are considered to be two in hand or two strands of a conductor or two wires in parallel. When counting the turns in a coil, the number of wires counted must be divisible by the number of strands or number of wires in hand. This is the actual turns of the coil. For example, if 36 wires are counted in the coil and it is wound two in hand, the actual turns will be $36 \div 2$, or 18 turns. Multiples of small wires are used in motors because they are easier to form than is one large wire.

Figures 1-54 and 1-57 are single voltage. The terminal lead markings for single-voltage run windings are T_1 and T_4. A single-voltage start winding is numbered T_5 and T_8. Single-voltage start windings are usually one circuit.

When four leads are connected to the run winding, it is a two- or dual-voltage connection. The leads are labeled T_1, T_2, T_3, and T_4. One-half of the groups are connected between T_1 and T_2, and the other half between T_3 and T_4, as illustrated in Figure 1-58. This winding is connected in series for high voltage and is a one-circuit connection, as illustrated in Figure 1-59. The low-voltage connection shown in Figure 1-60, is a two-circuit or parallel connection. The connections illustrated in Figures 1-58 and 1-60 are called a one- and two-circuit connection. Figure 1-61 is a two- and four-circuit diagram. As stated before, one-half the coil groups must be between T_1 and T_2, and the other half between T_3 and T_4. There

can be more than one circuit between these leads. The number of circuits possible between leads will be any number that will divide evenly into the pole groups between the leads.

The preceding diagrams all are short jumper. Short jumper and long jumper are explained on pages 19 and 20.

Another connection commonly found is the layered winding. The coil groups are wound two in hand, but the wires are separated, and the coil group then has two circuits, as illustrated in Figure 1-62. Figure 1-63 shows this type of coil group in a one-circuit diagram. A layered four-pole winding has eight separate coil groups. The number of connections possible for single voltage are one, two, four, and eight-circuits. The dual-voltage possibilities are one- and two-, two- and four-, and four- and eight-circuit connections. Figures 1-63 through 1-66 show single-voltage connections. Figures 1-67 through 1-69 show dual-voltage connections.

Assuming that the windings have been burned or softened with chemicals, a connection is identified as follows:

1. Mark the location of the leads on the stator with a chisel and make a sketch of it on the data sheet, as shown in Figure 1-70.

2. Count the number of pole groups in the run and the start windings, and record it.

3. Lift or loosen the start-winding leads and the cross-connections to determine how many circuits it has. Start windings are usually connected in one circuit, for one voltage, but some are connected for two voltage, as in Figure 1-71. Another connection is predetermined rotation (in Figure 1-72) or internally connected to the run winding (Figure 1-73).

Figures 1-74 and 1-75a and b are examples of split-phase circular diagrams. Figure 1-76 is a straight-line diagram of a split-phase motor. Notice the connections are the same as for the capacitor-start motors except that the capacitor is excluded. In an actual motor, the split-phase start-winding wire size is smaller and it has fewer turns than in the start winding of a capacitor-start motor. Because of this, adding a capacitor to a split-phase motor will not give it a starting power comparable to the starting power of a capacitor-start motor. Figures 1-77, 1-78, and 1-79 show some of the connections that may be encountered.

4. The jumpers, or crossover connections, from pole group to pole group are connected in two ways, long jumper and short jumper. Each pole group (except consequent pole, which will be explained later in this chapter) is connected so that the current will flow in the direction opposite to that of the pole groups adjacent to it. Short jumper means adjacent groups are connected in series or in parallel in the same circuit, as shown in Figure 1-77. This connection is also called short throw, top to top (T to T), or bottom to bottom (B to B). Long jumper means that the pole groups of the same polarity are connected in series or in parallel in the same circuit. Figure 1-80 shows a one-circuit run winding, and Figure 1-81 shows a two-circuit run winding. Both are one-voltage connections. Figures 1-79, 1-82, and 1-83 are dual-voltage connections. Long jumper connec-

tions are sometimes called long throw or top to bottom (T to B). This should be noted on the data sheet.

5. Count the leads going to the run winding. Two leads mean one voltage, and four leads mean dual voltage. Note this on the data sheet.

6. Count the run pole groups fastened to each lead. If the motor has two leads, it is single voltage, and the number of pole groups fastened to each lead is the number of circuits the winding contains. If there are four leads, the motor is dual voltage. Count the pole groups fastened to each lead. If there is one pole group, the connection is in one and two circuits, and if there are two pole groups, the connection is in two and four circuits. This information should be noted on the data sheet.

INSULATION TEMPERATURE

The insulation temperature classes are

Old class	*New class*	*Limiting temperature*
A	105	105°C
B	130	130°C
F	155	155°C
H	180	180°C

Of these, the most popular—and the majority—are Class 155 and Class 180. Using Class F on a motor that is rated Class B upgrades the motor and will increase its thermal life expectancy. But operating a motor at a higher temperature than its class will shorten its life. Insulation, being a form of plastic, is always curing and will become more brittle with time. If the temperature is increased, the time or life will be shortened. Insulation in motors needs to be resilient, as the copper wire heats and expands as the motor starts and runs. But the insulation and stator laminations will expand at a different rate. The insulation must stretch and contract with the wire, and when the insulation becomes brittle, it will develop fine cracks and expose the wire to contaminants. The contaminants (carbon, moisture, or any conducting material) will conduct current, resulting in charring. This, in turn, conducts even more current, which will lead to a complete insulation breakdown.

The temperature classification rating for a motor is based on the temperature of the hottest area in it. This area is in the center of the slot, near the thickest part of the iron and in the center of the pole group. Much of the heat is transferred out of the core by the coils themselves. The internal fan forces air over the coils and carries the heat away. The iron core carries the rest of the heat to the shell of the motor where it dissipates into the surrounding air.

When selecting the proper insulation class, the same class should be used for all components. If Class 155 is selected, the slot liner, the slot separator, the sleeving, the magnet wire, the lead wire, and the tie cord all should be Class 155. Nearly all magnet wire used in the repair industry today is Class 180, and to stock any other classes of magnet wire would make inventory cost prohibitive.

FORMING SLOT LINERS

There are two types of slot-liner formers available from electric motor parts suppliers. One cuts and creases the paper with one stroke of the handle, as shown in Figure 1-84. The other, in Figure 1-85, will only crease the paper. The paper must be cut to the exact width and length before going through the former. This type of format has no limit as to length, and the pressure of the creaser can be varied for different thicknesses of insulation.

After selecting the proper class insulation, cut a strip that is 3/8 inch wider than the length of the stator core. At this point a taping machine, as shown in Figure 1-86, can be used. When the ends of the slot liners are taped, they are less likely to tear from the pressure of the coil when there is a tight fit.

It is important that the slot liners fit exactly. If the sides of the liner are too short, there is a good chance that the winding will ground to the stator. And if the sides are too long, the paper will block the slot opening and make inserting the wire very difficult. Measuring for the slot liner with a metric ruler is much faster than using an inch ruler.

Before the slot liners are inserted, check each slot for sharp burrs or fused copper. Anything that can puncture the slot insulation must be eliminated. All copper must be ground or filed from the slot and the laminations cleared to prevent hot spots from eddy currents. Sometimes it is necessary to chisel out some of the teeth. But with larger motors, if too many teeth are removed, it will be necessary to restack the laminations and stagger the missing teeth evenly throughout the stator.

REWINDING

There are two types of coil forms used to rewind single-phase motors, lap and concentric. Lap winding will be discussed in Chapter 3. The concentric form used to rewind most single-phase motors is used by manufacturers because it can be formed by machine, thus saving labor costs. In the repair shop, the concentric coils are formed on a winding head (Figure 1-87) and placed in the stator by hand. The run or main winding is placed in the bottom of the slot, and the start winding is placed on top of the slot. Insulating between the two windings is optional; the accepted voltage between coils without insulating is 150 volts. If insulation is used, a strip of insulation is placed on top of the run winding in the

slots shared with the start winding. These are called separator papers and are shown in Figure 1-88. If using the separator paper makes the wires fit too tightly, it is better to leave it out than to tamp the wire too much. When all the wire is in place in the slot, a fiber wedge is inserted, as shown in Figure 1-88. All insulation used should have a temperature class that is equal to or higher than the nameplate rating.

Setting up the winding head for the concentric coil is done in the following order:

1. The first step is to form a single wire to fit the inner coil of the group. It must fit snugly but not bend the slot liner. Place the pattern wire on the step of the winding head that is nearly the same width. Open the head to fit the pattern wire tightly, and make note of the setting number, as in Figure 1-87. Next, skip at least one step on the head and form a pattern on it (Figure 1-89). Collapse the head and try both pattern wires in the proper slots. There should be enough room between the two patterns to contain all the turns of the smaller coil after the pattern wires are squared and shaped (Figure 1-90). If these two pattern wires are satisfactory, make the rest of the pattern wires and fit them as in Figure 1-91. If there is not enough room between the coils to contain all the turns, the coils will stack on top of the smaller group and make it difficult to insert the start winding in the slots. The finished coil should take the shape shown in Figure 1-92. It should come out of the slot, to the edge of the slot liner, bend toward the other side, and at the same place bend down and over so the start winding can easily be placed in the proper slots. Write the step numbers selected on the data sheet, and also note the setting dimension. After the first step number, write the number of turns in the smallest coil. After the second step number, write the sum of the smallest coil and the next coil. Next add the number of turns of the third coil in the group to this number and place it after the third step number. These numbers show when to stop the winding machine and feed the wire over to the next step.

2. The required number of turns is wound on the steps of the winding head, starting with the smallest step. Tie the coils with string or twist ties to keep the turns in position (Figure 1-93), and remove the group from the winding head.

3. The coils are now laid in front of the stator with the leads toward the motor and the ties away from the you. Pick up the inside coil (the smallest), place it in the stator bore, and center the coil between the thru-bolt holes. Feed the wires into the slots starting with the coil side nearest you, as shown in Figure 1-94. It is not uncommon to have to place the wires in the slots one at a time. After each coil side is in the slot, place a separator paper over it to keep the wires from coming out of the slots. The separator paper should be about one-half inch longer than the slot liner. Pick up the end of the second coil as you would the page of a book and place it in the bore, again first inserting the turns of the side nearest you. Determine which coils do not share the slot with the start winding and place a fiber wedge instead of separator paper over these coils. Shape the ends of the coils as they are inserted, and after each coil is in place, shape it with a soft clean hammer. The job will be neater if each coil is shaped individually instead of the

whole group at once. If the ends of the coils are to be insulated, cotton or glass tape can be put in place at this time.

After all the run coils are in place, shaped, and insulated, the start winding can be inserted, as shown in Figure 1-95. Each coil of the start winding will be held in place by a slot fiber. These fibers should be the same length as the slot liner.

Connecting Procedure. After the windings are in place and shaped, the coil-lead wires are separated, as in Figure 1-96. The stator is now ready to be connected. The connecting should start at the side nearest you (six o'clock) and proceed to the right in a counterclockwise direction (Figure 1-97). This is the same as reading a circuit diagram from left to right. Starting at the one o'clock position and proceeding clockwise will accomplish the same thing but is difficult when connecting a larger motor.

Regardless of the number of poles, it is essential that adjacent ones be of opposite polarity. This is accomplished by connecting them in such manner that the current will flow through the first pole in a clockwise direction and through the second pole in a counterclockwise direction (Figure 1-98) and likewise in alternate directions through the remaining poles.

It should be remembered that if the run winding is connected in one circuit or in series, the start winding must be connected in this same manner. There are exceptions to this, but they are not often encountered.

Series Connection for Four Poles of the Run Winding. Refer to Figure 1-98 and connect the wires as illustrated, namely, the end lead of Pole 1 to the end lead of Pole 2. Next, connect the beginning lead of Pole 2 to the beginning lead of Pole 3, as shown in Figure 1-99. Continue, as illustrated in Figure 1-100, by joining the end lead of Pole 3 to the end lead of Pole 4. The power-line leads are then connected to the beginning lead of Pole 1 and the beginning lead of Pole 4.

For the sake of simplicity, the above-noted connections may be shown by representing each pole as a rectangular block, as in Figures 1-101, 1-102, and 1-103.

For comparison, the entire run winding of a 36-slot, four-pole motor is illustrated in Figure 1-104, showing both the detailed winding and the simplified form. Notice that each pole is wound in the same manner but that the poles are connected so that alternate polarity is maintained in adjacent poles.

In order to determine whether the polarity of the poles is correct after the connections have been completed, a low-voltage direct current is connected to the winding, and a compass is moved inside the stator from one pole to the next. If the connections are correct, the compass needle will reverse itself at each pole.

Series Connection for the Start Winding. The poles of the start winding are connected so that they too alternate in polarity. The method of connecting them to one another is the same as that described above for the run winding. The only difference is that the stationary switch is placed either in series with the lead from

Pole 4, or between Pole 2 and Pole 3. Figures 1-105 and 1-106 show the proper connections for both the run and start windings, Figure 1-105 having the stationary switch at the end of the start winding and Figure 1-106 having it in the center of the winding. Figure 1-107 represents both windings placed in circular form as they would actually be inside the stator.

The connection drawing can be shown in simpler form by making a schematic diagram, like that in Figure 1-108. Such a diagram does not indicate the number of poles, but it does show how the lead wires from the windings are connected to the power line. It is seen that two wires are brought out directly from the run, winding, and likewise, two wires are brought out from the start winding. The direction of rotation of the motor can easily be changed by reversing the lead wires of either the run or the start winding. The run-winding leads are marked T_1 and T_4. The start-winding leads are marked T_5 and T_8. Figure 1-109 shows the method of connecting the leads for clockwise and counterclockwise rotation.

A six-pole motor is connected in the same manner as is a four-pole motor, except that two more poles must be added. Figure 1-110 shows a connection diagram of a six-pole, capacitor-start motor.

MAKING CONNECTIONS

Pole group-to-pole group and line-lead connections are made in the following order:

1. Select sleeving that is the right temperature and size.
2. Measure and cut the sleeving to the right length.
3. Install sleeving and twist wires together.
4. Weld or solder the splice.
5. Cover the splice and tie down all connections.

The temperature rating of the sleeving should be the same as that for the rest of the insulating system. Sleeving has a size number that coincides with the wire size. A no. 14 wire will fit into a size 14 sleeving. A splice should take as little space as possible, as bulky, oversized connections can become a problem when the end room is restricted.

After choosing sleeving of the right size and temperature rating, measure the length for a connection. Figure 1-111 shows this being done. The wire should be covered with sleeving to the place where it is secured. This place may be a slot or where the wire is taped to the coil. Allow extra length so that the splice can be adjusted for the best position when being tied down. Cut the sleeving to the right length and then cut it into two parts. It may be desirable to cut it so that one piece is shorter than the other, so that the location of the splice will be in the best spot. A piece of sleeving that will cover the completed splice is cut next. This sleeving should be five to six sizes larger than the sleeving used on the wire. Cut the cover

sleeving at least one inch longer than the splice. Slide the cover sleeving over one of the wires. They now are ready to be twisted tightly together. Figures 1-112a and b show a completed splice. The length of the splice should be from one to two and one-half inches long, depending on the size and number of wires in the splice. Large splices with many wires in multiple should be two and one-half to three inches long. Figure 1-113 shows the winding being tied down after the connections and leads are finished.

Welding Connections

Line-lead and pole group-to-pole group connections are made by means of (1) solder, (2) silver solder, (3) phosphorus-copper, (4) melting together, and (5) pressure sleeve. The requirements and things to consider when making a splice are

1. A good electrical connection that includes all the strands and is equivalent in size laterally to the circular mil area of all the coil-group wires.
2. The time it takes to complete the connection.
3. The expense of the material used in making the connection.
4. A smooth splice that will not pierce the insulation.

1. Lead-tin solder makes the most dependable connection with stranded lead wire. Solder impregnates the splice, filling all the space between the wires. Soldering is also the most time-consuming method, as all insulation must be cleaned from the magnet wire before it can be soldered. There are several types of special wire-skinning tools available from electric motor parts suppliers.

2. Silver soldering is a quick method of welding connections. It is not necessary to use flux or to clean the coating off the wires. After twisting together the wires and trimming them off evenly, heat the ends of the wires with an acetylene torch. When they glow a dull red, apply the silver solder to the ends. It will flow into the splice. It is necessary to apply solder to only about one-half inch of the splice. Make sure all the strands are included in the weld. The soldering should be done as quickly as possible so that the heat does not char the sleeving. A large connection should be made with a wet rag wrapped around the sleeving and the lower end of the splice. After the splice has cooled, any sharp points or edges should be smoothed with a file to prevent them from piercing the insulating cover sleeve.

3. Phosphorus-copper is the preferred welding material because of its low cost. This material is used in the same way as is silver solder. Phosphorus-copper has a slightly higher melting point than silver solder does. It is available at most electric motor parts supply establishments.

4. Melting the wire together requires more skill than do the other methods. The flame of an acetylene torch is applied to the ends of the wires in the splice until they melt. This method works better when some of the insulation is scraped

off near the ends of the wires. The melted ends of the wires will flow together. Caution must be used not to burn the insulation beyond the splice. As with other methods, all sharp parts should be removed before the cover sleeve is put in place. This is the most economical method of making a splice.

5. The pressure splice is used mainly with aluminum wire. The wires are inserted into a special sleeve and crimped with a tool designed for that purpose. Aluminum wire should be sealed at the splice to prevent corrosion. The sleeve will penetrate the coating on the wire and make a good electrical connection. As with all connections, the area that is joined electrically should be equal to or exceed the circular mil area of the wires being joined.

Testing the New Winding

After the rewinding, connecting, final shaping, and tying, make sure that the bore and thru-bolt holes are not obstructed by any wire or insulation. Also make sure that the end brackets, stationary switch, and cooling fan will not touch the winding. Next the windings and connections should be tested for shorts, grounds, open circuits, and incorrect connections. This must be done before the varnishing and baking. Any problems that are discovered at this time may be corrected easily. Detailed instructions for these tests will be found later in this chapter under "Troubleshooting and Repair."

Baking and Varnishing

When all the connections between the poles of the windings have been completed and tested and the flexible leads to the power line attached and tied, the stator should be placed in a baking oven at a temperature of approximately 250°F and preheated for a short period of time, approximately one hour. This removes moisture from the windings and will increase the penetration of the varnish. The stator is then dipped into a container of insulation varnish. It is important to remember that the varnish must be thin enough to penetrate the winding and thick enough to leave an adequate film when baked. The varnish may thicken because of evaporation of the thinning fluid. If this happens, use a thinner recommended by the manufacturer. The purpose of varnish is to (a) secure the wires so that they don't vibrate and short to one another, (b) provide another coat of insulation for the whole coil group, and (c) provide a path for heat to escape from within the coil.

Air pockets in the slots allow movement of the wires which will eventually wear through the insulation and cause shorting between the turns. These voids can also thermally insulate the winding, inhibiting the heat transfer from wire to core and shorten the life of the insulation. It is important that the winding be allowed to soak until all bubbling has stopped. The large service centers use the vacuum pressure impregnation (VPI) system of varnishing windings. The winding is lowered into a special tank; the tank is sealed; and a vacuum is applied. This removes moisture from the winding. While it is still under vacuum, the

varnish is slowly allowed to rise from the bottom of the tank and cover the winding. The air trapped in the slots is expanded from being under a vacuum, and after the vacuum is released, it shrinks, pulling the varnish in. Then pressure is applied to the tank, forcing the bubbles to shrink even smaller and nearly eliminating them. The winding is then baked until cured.

Most bake-type varnishes are thermal setting; that is, the winding must be heated to a prescribed temperature for a given length of time. If the temperature is not reached, the varnish will not set up, no matter how long it is baked. The temperature class of most varnishes is Class 155 or Class 180.

There are many other types of varnishes. One type is made for hermetic motors and is not affected by the oil or refrigerant. For extra protection of the end coils, there are air drying and the butter-on varnishes. There is a two-part flow-type that is shown being applied in Figure 1-114 to a three-phase stator. This type is made up of a resin and a reactor. Once the two are mixed, they chemically react, start to heat, and harden in about 30 minutes. There are other two-part types that need a short bake cycle to complete the cure. The temperature class selection must be compatible with that of the motor design. It is important to have proper ventilation when using all varnish methods, and to follow the dip and bake procedures recommended by the manufacturer.

MOTOR OVERLOAD PROTECTIVE DEVICES

Most overload devices used on single-phase motors are thermally operated and protect against dangerous overheating due to overload, failure to start, and high temperatures. The protector is mounted in any convenient location inside the motor housing or in the junction box on the side. Essentially, this device consists of a bimetallic element connected in series with the line. This element is made of two metals that expand at different rates when heated. These are bonded together, so that when the entire element is heated, it will bend and open the circuit to the motor (see Figures 1-115 and 1-116). The heat causing the element to bend is created by the current that goes through an auxiliary heater coil placed under the bimetallic strip and connected in series with the motor windings.

A popular type of thermal device consists of a round, dish-shaped, bimetallic disc, with two contacts on diametrically opposite sides bearing against two stationary contacts, marked P_1 and P_2 and an auxiliary heater marked P_3. The heater is mounted directly underneath the bimetallic strip and in close proximity to it. Figure 1-117 shows the closed and open position of the disc.

When an overload occurs, the current flows through the heater and will produce sufficient heat to cause the disc to snap quickly and open the contacts and thereby open the circuit, stopping the motor.

On some types, the contacts automatically close when the bimetallic element cools. On other units, a reset button must be operated manually to restore the motor to operation.

This type of thermal unit can be used for single- and dual-voltage motors. In the single-voltage motor, terminal P_2 is not used. The heating element and disc are connected in series with the entire motor winding. This is illustrated in Figure 1-118. In a dual-voltage motor, the heating element is connected in series with half the main winding for lower voltage and the entire winding for high voltage. This is because the current on high voltage is half that on low voltage. An illustration of the connections is shown in Figure 1-119.

The terminal P_1 is always accessible from outside the motor. P_1 is always connected to a line by itself. All motor leads must be connected to P_2 or P_3. P_3 is usually connected to the run windings. P_2 is sometimes identified as a brown wire with no label. The current going through P_2 will not cause the thermal protector to open. P_2 is usually not used in single-voltage motors and is not used in dual-voltage motors when the connection is for high voltage. P_3 is usually an internal connection going directly to either T_1 or T_4. In some cases, T_1 or T_4 is connected to P_3 internally and also brought out, as shown in Figure 1-118.

The temperature of the air around the thermal protector has a bearing on how soon it will open when there is an overload. Because of this, a thermal protector is rated differently if it is located inside the motor than if it is located outside, in the junction box of the same motor.

Thermal protectors are designed to protect against overloads, as a short will usually destroy the heating element. If terminal *2* does not light to terminal *3*, then the heater element is open, and the thermal protector must be replaced. The heater element is always rated for the high voltage amperes in a dual-voltage motor.

There are other types of thermal devices in use today. One of these utilizes a bimetallic unit heated by the current flow through the unit itself. This type uses a toggle link to open the contacts. This unit is mounted on the terminal plate, which also serves as a connection block for the winding leads. The operation is as follows: When a condition of excessive temperature or current occurs, the bimetal arm is heated and deflects in a direction tending to open the contacts. The contacts will remain closed, however, until the downward force of the bimetal arm overcomes the opposing force of the toggle link and snaps open the contacts. This type is shown in Figure 1-120.

Thermal protectors of special construction can be embedded in the stator windings to protect the motor from excessive winding temperatures. These protectors have a snap-acting disc with normally closed contacts. The disc is operated both by the current passing through it and by heat received from the windings. When the disc's temperature reaches a predetermined calibration point corresponding to the maximum safe limit of the winding, the disc snaps open to interrupt the circuit. When the winding temperature returns to a normal safe limit, the protector resets automatically. Thermal protectors are frequently used with hermetic motors, and in such cases, the protectors are installed in the end windings and located for the best possible heat transfer between the winding and thermal unit, that does not damage the insulation on the motor winding. It is important to

exercise care in assembly, as additional forming of the winding for location of the protector may injure or weaken the insulation on the winding.

SCHEMATIC DIAGRAMS OF CAPACITOR-START MOTORS

The schematic diagrams in Figures 1-121a, b, c, d, and e are reproduced through the courtesy of NEMA and show the terminal markings of single- and dual-voltage capacitor-start motors with and without a thermal protector. These diagrams are part of the NEMA Standards Publication MGI of April 1968. Data on terminal connections will be found on pages 15 and 16 of this chapter.

CONNECTIONS OF CAPACITOR-START MOTORS

Some of the many types of capacitor motors are listed below. Each has its own characteristic connection of the windings. Some of these types are designed to operate on one voltage, some on two voltages. Many are externally reversible, and others are reversed internally. Each of the following motors is described, and a diagram shows its operation:

1. Single-voltage, externally reversible.
2. Single-voltage, nonreversible.
3. Single-voltage, reversible with overload protector.
4. Two-voltage, reversible.
5. Two-voltage, reversible with overload protector.
6. Single-voltage with current relay.
7. Single-voltage with potential relay.
8. Two-voltage with potential relay.
9. Single-voltage, three-lead, reversible.
10. Single-voltage, instantly reversible.
11. Single-voltage, two-speed.
12. Single-voltage, two-speed, consequent-pole.

In the schematic diagrams of these motors, the leads with numbers will be coming out of the motor. This is typical of larger motors. Most smaller motors have leads connected to the terminals mounted on the stationary switch, inside the motor. In all of the following capacitor-start motors, electrolytic capacitors are used. In all single-voltage capacitor motors, the main or run-winding terminals are marked T_1 and T_4, and all start-winding terminals are marked T_5 and T_8. Standard markings are described and illustrated on pages 15 and 16 of this text. If the start-winding leads are accessible for reversing, the leads will be given the numbers T_5 and T_8. If they do not have a number, they will be connected to the run-winding leads inside the motor and will not be accessible.

1. Single-Voltage, Externally Reversible Capacitor-Start Motor. This motor has four leads that are accessible, two from the run winding and two from the start winding. These four wires must be separately available if external reversing is desired. Internally, the start winding is connected in series with the stationary switch and the capacitor. Figure 1-122 shows the motor connected for clockwise rotation, and Figure 1-123 shows the same motor connected for counterclockwise rotation. As the illustrations show, to reverse this or any other type of capacitor motor or split-phase motor, it is necessary only to reverse the start-winding leads with respect to the run-winding leads, or vice versa. Just as in other types of motors, the number of poles in this motor determines its speed: the more poles there are, the lower its speed will be; and the fewer poles there are, the greater its speed will be. The poles are connected in series or in parallel; care must be taken to produce alternate polarity in connecting the poles. The four-pole motor is the most common, and therefore diagrams of four-pole motors will be shown. Figures 1-124 and 1-125 illustrate a four-pole capacitor-start motor with a one-circuit start winding and a one-circuit run winding. Figure 1-126 shows a four-pole, two-circuit capacitor-start motor with a one-circuit start winding and a two-circuit run winding. Figure 1-127 shows a four-pole, two-circuit, capacitor-start motor with a two-circuit start and a two-circuit run winding.

2. Single-Voltage, Nonreversible Capacitor-Start Motor. If the start-winding leads are connected internally to the run-winding leads, the direction of rotation of the motor cannot be reversed unless the motor is taken apart and the leads reversed. Some motors are made in this manner because their application requires just one direction of rotation. Figure 1-128 shows the circuit of this type of motor with two external leads. Single voltage can mean low voltage (120 volts) or high voltage (240 volts). Some manufacturers connect the start winding to the center connection of the run winding, as shown in Figure 1-129. This limits the voltage applied to the start winding to one-half the line voltage. The capacitors used with this connection are rated for use on low voltage.

3. Single-Voltage, Reversible Capacitor-Start Motor with Overload Protector. Very often capacitor-start motors are equipped with an overload protector device. The function of the overload device was explained earlier under "Motor Overload Protective Devices." The overload device is always connected in series with one of the lines. P_3, which is the heater element terminal of the device, is always connected in series with the run winding, as shown in Figure 1-130. Some manufacturers connect T_1 to P_3, and others connect T_4 to P_3. Single-voltage motors usually do not use P_2, and both the start and run winding are connected to P_3. The current of the start winding flows so briefly that it is not considered to affect the overload device. P_2 sometimes has no number but is identified by being a brown wire. When ordering a replacement overload device, include all nameplate data and all numbers appearing on the old device.

4. Two-Voltage, Reversible Capacitor-Start Motor. A two-voltage or dual-voltage capacitor-start motor can be operated on either of two voltages, usually 120 or 240 volts. This type of motor generally has a main or run winding of two sections and a start winding of one section. In some larger motors, a two-section or dual-voltage start winding is used. The one-section start-winding will be discussed first.

To change from one voltage to another, it is necessary to bring out four leads from the run winding, two from each section. These sections are marked T_1, T_2, and T_3, T_4. If the motor is to operate on 120 volts, the two sections of the run winding are connected in parallel, and the start winding is connected in parallel also, as shown in Figure 1-131. If operation on 240 volts is desired, the two sections of the run winding are connected in series. The start winding is connected across one section of the run winding, thereby receiving 120 volts, or one-half of the line voltage, shown in Figures 1-132 and 1-133. A dual-voltage motor using this connection will always have the lower voltage potential across the start winding, regardless of the line voltage, and will always be connected in parallel with one or the other of the run-winding sections.

Small, dual-voltage motors sometimes have colored wires instead of numbers to identify the leads. Figure 1-134a and b shows this method of identification connected for high voltage and low voltage.

Some two-voltage capacitor-start motors have a dual-voltage start winding. Figure 1-135 shows this connection using one set of switch contacts and connected for low voltage. Figure 1-136 shows the high-voltage connection for this motor. Figure 1-137 shows a second method, using two switch contacts. The switch connection is made internally, in series with T_6 and T_8. The capacitors used in both types of dual-voltage start-winding connections are always rated as low voltage and are connected in series with T_6 and T_8. Figure 1-137 shows the low-voltage connection, and Figure 1-138 shows the high-voltage connection.

REWINDING THE TWO-VOLTAGE CAPACITOR-START MOTOR

The start winding of a dual-voltage capacitor-start motor is identical with that of a single-voltage motor and is wound in exactly the same way. The run winding, however, consists of two sections and may be wound in any of three ways. One method consists of winding the poles in the same way as for the single-voltage motor and connecting the poles in two sections. Each section contains one-half the poles. Two wires are brought out for each section for changing voltage. Figures 1-131 and 1-132 show this method. The poles may be connected short jumper (adjacent poles in the same circuit) or long jumper (like poles in the same circuit).

Another method is shown in Figure 1-139. With this method, one-half of all the poles are connected in one section, and the other half is connected in the

other. Each section can be insulated from the other. This method may also be connected long or short jumper.

The most popular method is to wind both sections, as described above, at the same time and to insert them in the stator without insulation between them. This method takes much less time. But without an insulation barrier between sections, extra care must be taken not to scratch the insulation of the wire or they may short together. The accepted allowable voltage between wires with only the coating on the wire as insulation is 150 volts. Extra insulation is recommended for over 150 volts.

5. Two-Voltage, Reversible Capacitor-Start Motor with Overload Protection. The two-voltage capacitor-start motor described in Figure 1-131 is shown in Figure 1-140 with an overload protector and connected for low voltage. Some manufacturers solder either T_1 or T_4 onto P_3 internally. In this case, T_1 is soldered to P_3 and is not accessible. P_1 is considered to be the same as T_1. When the low-voltage connection is used, P_2, which is the brown wire in some motors, is connected to the start winding and the remaining section of the run winding. The current of the remaining run-winding section should not go through the heater element. Figure 1-141 is a schematic showing the current flow for this circuitry. Figure 1-142 shows this motor connected for high voltage and shows the current flow. The brown wire, or P_2, is either insulated and not used or can be connected to a start-winding wire. The nameplate amperes for the high-voltage connection are always one-half the amperes for the low-voltage connection.

6. Single-Voltage, Capacitor-Start Motor with Current Relay. Motor-starting relays are used instead of centrifugal switch systems for many split-phase and capacitor-start motors. These relays are standard equipment for hermetically sealed motors in refrigeration units, pumps, table saws, and many other definite-purpose machines. It is impractical to use a centrifugal switch system on hermetically sealed motors, because servicing or replacing the switch components is nearly impossible. For this reason, an external magnetic relay is used. The relay may be located on, near, or outside the motor. It is used to disconnect the start winding from the circuit when the motor reaches approximately 75 percent of full speed. Figure 1-143 shows this connection. The current relay operates on the principle that the initial inrush of current in the run winding at the start is much greater than at full speed. The relay mechanism consists of a magnetic coil and two normally open (at rest) contacts. The coil is connected in series with the run winding. The coil is wound with wire that is as large or larger than the run-winding wire because the run-winding current continuously flows through it. The contacts of the relay are connected in series with the start winding and the capacitor. When line voltage is applied, the coil becomes sufficiently energized, because of the high current of the run winding, to cause the contacts to close. Consequently, when the motor is thrown across the line, both the start and run windings are energized, and the motor will start. At approximately 75 percent of full speed, the current of the run winding will decrease, and the amount of

current flowing through the coil will not be enough to keep the contacts closed. When the contacts open, the start winding is disconnected from the circuit, allowing the motor to operate on the run winding only.

Positioning the current relay properly is important. If the contact mechanism is not spring loaded, the contacts will depend on gravity to open them, and the relay will be marked "this side up." Even a few degrees of tilt can keep the contacts from falling open. These motors are not usually connected for reversing, as to reverse them, it is necessary to bring four leads out of the motor.

A disadvantage of this type of relay is the possibility that short-pulse types of overloads may cause the magnetic coil to operate and connect the start winding across the line during each pulse. This will overheat the start winding, and it may become shorted.

A relay coil must be designed for the amount of run current of the motor with which it is used. If the relay coil is designed for a lower current than the motor requires, the contacts will not open. But if the relay coil is designed for a higher current than the motor requires, the contacts will not close. Figure 1-144 shows this motor connected to a two-terminal overload protector. Figure 1-145 shows a two-voltage connection using the current relay. Like the heater element of a thermal protector, the amperes through the coil of the current relay must be the same with either high or low voltage. The wire of the coil must be as large as the motor winding wires that are in series with it.

*7. **Single-Voltage, Capacitor-Start Motor with Potential Relay.*** The function of the potential relay, as with the current relay, is to disconnect the start winding from the line when the motor reaches a predetermined speed. Figure 1-146 is a schematic of the circuitry.

The relay consists of a magnetic coil that is connected in parallel with the start winding, and a set of normally closed contacts that are connected in series with the start winding. When line voltage is applied to the motor, both windings will receive line voltage, and the motor will start. As the rotor speed increases, the voltage across the start winding will increase above line voltage. At approximately 75 percent of full-load speed, the voltage across the start winding will become high enough to make the relay function. The relay opens the normally closed contacts that are in series with the start winding, disconnecting the start winding. The normally closed contacts remain open during normal operation because of the high voltage that is induced into the start winding. This induced voltage comes from the magnetic lines of force of the rotor's cutting the wires of the start winding. The relay is designed to function at 140 percent of line voltage. Figure 1-147 shows the current flow after the contacts open.

It is important that the circuit containing the potential relay and the start winding not include the capacitor. If a capacitor is in this circuit, the relay will function before the motor reaches the right speed. The motor will not be able to pull its rated load and will cycle at a low speed until it burns out or the circuit protector opens.

When a capacitor-start motor with a potential relay has a flywheel-type load, the relay contacts may open and close several times after the motor is shut off. This is called *contact flutter* and will deteriorate the contacts more quickly than normal. The flutter can be lessened by soldering a 15,000-ohm resistor across the capacitor's terminals. To prevent the flutter completely, the motor may be connected to a three-pole switch, as shown in Figure 1-148. This will isolate the capacitor when the motor is shut off, opening the start-run circuit.

The potential relay can replace a centrifugal device–stationary switch system. The contacts of the relay have a horsepower rating that should be considered when this is done. The coil is designed to be used on 120-volt or 240-volt start windings and is designed to function at 140 percent of the start winding's rated voltage. The coil can be connected across any portion of a start winding that will produce a voltage high enough to make the relay function.

8. Two-Voltage, Capacitor-Start Motor with Potential Relay. If a motor is dual voltage, the potential relay must be rated for the lower voltage. Figure 1-149 is a dual-voltage motor with a low-voltage potential relay connected across the start winding.

Figure 1-150 is a motor with a 240-volt start winding that is controlled by a 120-volt potential relay. When taking data, it is important to trace the wires of the relay coil to the winding. This will determine the voltage of the relay coil. If a low-voltage relay is connected across the complete start winding of Figure 1-150, it will burn out. If a potential relay has no voltage rating marked on it, its rating can be determined by applying 240 volts to it. If it closes, it should be rated as 120 volts. A potential relay rated as 120 volts will not close on 120 volts but will close if 240 volts are applied. A 240-volt potential relay will not close if 240 volts is applied; thus if the relay functions on 240 volts, it will be rated as 120 volts. Figure 1-151 is a straight-line diagram and a schematic of a large motor using two potential relays to control the start winding. This motor has a two-circuit start winding and a two-circuit run winding. The potential relays are rated for low voltage. The connection divides the current of the start winding between two sets of contacts.

9. Single-Voltage, Three-Lead, Reversible Capacitor-Start Motor. Any six-lead, dual-voltage capacitor-start motor can be a three-lead reversible motor. The motor must be used on high voltage only. Figure 1-152 shows how this is done. When T_5 is on L_1 with T_1, the current flow in the start winding will be as illustrated in Figure 1-152a. When T_5 is moved to L_2 with T_4, the current through the start winding will be reversed. Figure 1-153 shows a connection that is used on many motors that are five horsepower and larger. This connection is essentially the same as that in Figure 1-152, except that it shows where the connection is made internally and the leads T_2, T_3, and T_8 are not used. These larger motors are designed for use on high voltage only. Leads T_1, T_4, and T_5 are accessible in the junction box.

10. Single-Voltage, Instantly Reversible Capacitor-Start Motor. Under normal operating conditions, a capacitor-start motor must be brought to a complete stop before it can be started in the reverse direction, because the centrifugal device will not function until the motor has almost stopped. Because the start winding is out of the circuit when the switch is in the OPEN position, the reversal of the start-winding leads while the motor is running has no effect on the motor's operation.

Some capacitor-start motors have a reversing switch, which is connected as shown in Figure 1-154. This switch has three blades, or poles, that move as one unit to either of the two positions. In one position, clockwise rotation of the motor is provided, as shown in the illustration; in the other position, the leads of the start winding are reversed for counterclockwise rotation. Pushbutton manual, magnetic reversing starters or drum starters are utilized for reversing purposes.

To reverse this type of motor, it is necessary to wait until the motor slows down to a point at which the centrifugal device causes the stationary switch contacts to connect the start winding to the line.

INSTANT REVERSAL. Certain types of loads require instant reversal. To permit instant reversal while the motor is operating at full speed, a relay is placed in the circuit to short-circuit the stationary switch contacts and connect the start winding in the circuit in the opposite polarity.

Figure 1-155 shows such an instantly reversible capacitor-start motor with a reversing switch. At rest, the double-contact stationary switch is in the START position, which places the start winding and the capacitor in series across the line. At the same time, the coil of the normally closed relay is connected across the capacitor. With the manual switch in the FORWARD position, the run winding is connected across the line; the start winding and capacitor are in series across the line; and the relay coil is connected across the capacitor.

The voltage developed across the capacitor is applied to the relay coil, causing the normally closed relay contacts to open. As the motor starts and its speed increases, the stationary switch is thrown into the running position. This disconnects the capacitor from the circuit and leaves the start winding in series with the relay coil. This coil has high resistance and permits only enough current to flow through the start winding to keep the relay contacts open.

During the split-second interval while the switch is being thrown from FORWARD to REVERSE, no current flows through the relay coil; consequently, the relay contacts close. Then, when the switch reaches the REVERSE position, current flows through the now-closed relay contacts to the start winding, but in the opposite direction. This creates a torque in the direction opposite to rotation. As a result, the rotor is immediately brought to a stop, and the stationary switch returns to its starting position. This places the capacitor in series with the start winding, and the rotor starts turning in the opposite direction. The windings and rotor on this type of motor are designed to withstand the strain of quick reversal.

Figure 1-156 shows another instantly reversing method. The stationary switch has two sets of contacts, one for counterclockwise rotation and the other for clockwise rotation. The stationary switch also has a movable, spring-loaded lifting device for opening the contacts. The lifting device is constructed so that it cannot lift both contacts at the same time. The lifting device is moved under the contact that is in the direction of rotation by the spool of the centrifugal device. When the centrifugal device functions at 75 percent of full speed, it will release the lifting device. The lifting device will then open the contacts that are in line with it. Both sets of contacts on the stationary switch represent T_8 in this explanation.

For forward rotation, as shown in Figure 1-157, L_1 is connected to T_1 and T_5. L_2 is connected to T_4 and T_8-1. When the motor starts, the spool moves the lifting device in the direction of rotation and under contact T_8-1. At 75 percent of full speed, the spool releases the lifting device that opens T_8-1 and the start-winding circuit. T_8-2 remains closed. In Figure 1-158 the motor will be instantly reversed when T_8-1 is disconnected, T_8-2 is connected to T_1, and T_5 is connected to T_4. In this direction, T_8-1 is not used but is closed and ready for instant reversal. Figure 1-159 shows this motor connected to a four-pole, two-throw, center-off toggle switch. Magnetic controllers are usually used for this purpose.

11. Single-Voltage, Two-Speed Capacitor Motor. One way of changing the speed on a capacitor-start motor is to change the number of poles in the winding. To do this, two separate run windings are placed in the slots. The schematics (Figures 1-163a, b) will work with any two-run, one-start winding, pole combination.

The stationary switch has two sets of contacts that are normally closed (in the off or at-rest position) and one set of normally open contacts. One side of each set of contacts has a terminal or a means of connecting a wire to it. The other side of each of the three sets of contacts is a common connection to the movable part of the stationary switch. Figure 1-160 shows this arrangement. Figure 1-161 shows that the start winding and the matching (both rated at the same speed) run winding are fastened to one side of each of the normally closed contacts. The run winding also has a lead or terminal that goes to the high-speed terminal of the external speed-selector switch. The run winding that does not have the same number of poles as the start winding does is *always* fastened to the terminal of the normally open contacts. A lead or terminal from the common movable side of the three contacts will be fastened to the low-speed terminal of the external speed-selector switch. The opposite end of each winding will be fastened to a common wire or terminal. There is no NEMA standard for identifying the leads of multi-speed motors.

Figures 1-162a and b show the path that the current takes when the high speed is selected. The high winding is connected directly to the line. The current goes through both sets of normally closed contacts to the start winding. When the motor reaches about 60 percent of the high speed, the centrifugal device func-

tions and disconnects the start winding. The motor is now running at the high speed, as shown in Figures 1-162a and b.

When the low speed is selected, as illustrated in Figures 1-163a and b, the low-speed connection is energized by the external speed selector switch. The current flows from the common movable part of the stationary switch, through both normally closed contacts, and through the high-speed start and run windings. When the rotor reaches about 60 percent of the high speed, the centrifugal device functions. The high-speed start and run windings are disconnected, and the low-speed winding is energized through the now-closed, normally open contacts. The motor will now be running at the low speed, as shown in Figure 1-163b.

It is important that the centrifugal device does not function when the rotor is going faster than the low speed when the low speed is selected. If the normally open contacts close at 75 percent of the high speed, there will be a very high current for a short time that can fuse together the contacts. Centrifugal devices for two-speed motors will have a dual rating such as 1800/1200 or 1200/900. This indicates that they will function at less than 75 percent of the rating's highest speed.

In some cases, the three windings of a two-speed motor must be placed in the slots in a definite relationship to one another, as shown in Figure 1-163c. This is a typical layout of the pitch of the coils and their location in a 36-slot stator. This is a six-pole and an eight-pole combination, which illustrates how to take these data, should it be necessary.

12. Single-Voltage, Two-Speed Consequent-Pole Motor. This motor has one start winding and one run winding. When the poles are connected for the same polarity, the magnetic effect is to produce twice as many poles as there are wound poles. It is important that the span of the coil groups be the same as or slightly over the span used on the lower speed. There will be empty slots between the pole groups to accomplish this. The connection diagram is shown in Figures 1-164 and 1-165. It is possible to produce two speeds by arranging the connections between the poles in such a manner that when a speed switch is thrown in one direction, it will connect the poles so that they have alternate polarity and the motor operates as a four-pole motor. When it is thrown in the opposite direction, it will connect the poles so that they have the same polarity and the motor operates as an eight-pole motor by means of the consequent-pole method (see Figures 1-164 and 1-165). For the high speed, lead *B* is connected to one line wire, and leads *A* and *C* are connected together to the other line wire. Note that for this speed the run winding is connected two parallel. For the low speed, lead *A* is connected to one line wire and lead *C* is connected to the other line wire. For this connection, the run winding is connected in series consequent. For both speeds, the start winding is connected in series consequent. Figure 1-166 shows the magnetic path that is produced when the poles are of the same polarity. Figure 1-167 is a circular diagram of a consequent-pole motor. If *A* and T_5 are

connected to L_1, B is insulated, and C and T_8 are connected to L_2, the polarity of the groups will be as shown. All two-speed consequent-pole connections are long jumper in motors with four or more poles. The high speed is always twice that of the low speed.

Permanent-Split Capacitor Motors

Permanent-split capacitor motors are manufactured in sizes ranging from 1/20 to 35 horsepower. The smaller sizes are used on fans of all types. Because of the low inrush amperes, this motor can tolerate the stress of starting a flywheel-type load. The bearings, the windings, and the oil-filled capacitor are the only components that are subject to breakdown. This motor is comparable to the three-phase motor for low maintenance. Most of the smaller sizes cannot be repaired because of the way they are constructed. But the larger sizes are used in hermetically sealed refrigeration compressors and can be repaired.

A permanent-split capacitor motor is a capacitor motor having the same value of capacitance for both starting and running conditions. This motor is similar to the capacitor-start motor except for the following:

1. The capacitor and start winding are connected in the circuit at all times.
2. The capacitor is the oil-impregnated type and is of low value compared with electrolytic capacitors.
3. No centrifugal device or stationary switch is necessary.

This motor is quiet and smooth running and has a comparatively low torque. These motors are sometimes called single-value capacitor-run motors.

Some types of permanent-split capacitor motors are

1. Single-voltage reversible and nonreversible.
2. Single-voltage, special-duty reversible.
3. Two voltage reversible.
4. Two-speed single-voltage.
5. Three-speed single-voltage.

1. Single-Voltage, Reversible and Nonreversible Permanent-Split Capacitor Motor. This motor is similar in all respects to the capacitor-start motor, except that it does not contain a centrifugal switching system. It has two windings, one run, and one start. The start winding has more turns than does the start winding of a capacitor-start motor. The start and run windings are placed 90 electrical degrees from each other. An oil-impregnated capacitor may be mounted on or separate from the motor. The capacity is low compared with that of the electrolytic capacitors of the capacitor-start motors. A wiring diagram of a single-value capacitor motor is shown in Figure 1-168. To reverse this motor, reverse the start-winding leads in respect to the run-winding leads.

Figure 1-169a shows a nonreversible connection used on many special-duty applications. Some of these applications include furnace fans, window air-condi-

tioner fans, and hermetically sealed refrigeration compressors. The small-sized, permanent-split capacitor motors are constructed in such a way that repair is not economically feasible. In some cases, they cannot be disassembled without breaking the components.

The permanent-split capacitor motor is popular for sealed refrigeration compressors because of its low maintenance (see Figure 1-169b). Because of its low starting torque, the compressors occasionally become stuck. They can sometimes be loosened with a capacitor bank-starting unit, as shown in Figure 1-170. This unit will reverse the motor's starting torque by switching the single-pole, double-throw switch from one position to the other. The principle used here is explained next in "Single-Voltage, Special-Duty Reversible, Permanent-Split Capacitor Motors." Electrolytic capacitors rated for 250 volts are used in this starting unit. The amount of capacitance is selected in proportion to the compressor's horsepower. The unit is energized several times for two to three seconds in each direction. If this does not start the unit, it will be necessary to repair or replace it.

2. Single-Voltage, Special-Duty Reversible, Permanent-Split Capacitor Motor. This motor has a low starting torque and is used in dishwashers and control valves. It has two identical windings placed 90 degrees from each other. Both these windings are capable of being run windings. One serves as the run winding and the other as the start winding for one direction of rotation. During the reverse rotation, the one that formerly served as the run winding becomes the start winding, and the former start winding becomes the run winding. The winding that has the capacitor in series with it will have a leading current and thus become the start winding. These windings are formed in the same manner as those in the capacitor-start motor.

The principle of the motor's operation depends on the fact that the direction of the rotor's rotation is always from a start-winding pole to an adjacent run-winding pole of the same polarity. Tracing the circuit shown in Figure 1-171 shows that when the switch is in the forward position, the current travels through winding (b) to line 2. The current also takes a path through the capacitor and winding (a) to line 2. The capacitor gives winding (a) a leading current, and so it becomes the start winding. Winding (b) has a lagging current and acts as the run winding, causing rotation.

If the switch is in the reverse position (Figure 1-172), winding (a) becomes the run winding, and winding (b) acts as the start winding. The motor then rotates in the opposite direction.

3. Two-Voltage, Reversible, Permanent-Split Capacitor Motor. The connections of the motor, illustrated in Figure 1-173, differ from the dual-voltage capacitor-start motor only in that it has no centrifugal switch system. A two-section run winding and a one-section start winding are used. The run-winding sections are connected in series for high voltage. The start winding is connected in parallel with one of the run-winding sections, which limits the voltage to the start winding to one-half the line voltage. The low-voltage connection has all the

sections in parallel. These motors are wound using the same procedures that are used in winding the capacitor-start motors.

4. Two-Speed, Single-Voltage, Permanent-Split Capacitor Motor. Unlike the two-speed capacitor-start motor, this single-voltage motor does not require a change in the number of poles in order to decrease its speed. The speed of the rotor is never as fast as the speed of the stator's rotating magnetic field. The difference between these two speeds is called *slip*. When loaded, a decrease in the strength of the rotating magnetic field increases the slip and therefore decreases the speed of the rotor. The rotating magnetic field strength is decreased by adding turns to the run winding. This decreases the volts per turn of the run winding, thereby reducing the amperes of the run circuit. The result is the same as reducing the line voltage. The load remains the same so that the result is a lower speed because of the increase in slip.

Figures 1-174a and b show a two-speed winding connected for high speed and for low speed. The run winding has two parts, a high winding and a low winding. The high winding has a large number of turns and is designed to operate on line voltage. The low winding has fewer turns and is designed to be connected in series with the high winding. If the low winding is connected across the line, it will burn immediately. These motors can be wound for alternate pole or consequent pole. The high-speed part of the winding is inserted first and usually connected as one circuit. The second speed is inserted on top of the high speed. It also is usually connected in one circuit. The polarity of the low-speed poles must match the polarity of the high-speed poles with which they are wound. The wire size of the low-speed winding can be smaller than that of the high-speed winding because of the reduction in amperes when the low speed is used. The consequent-pole connection is used in some very low speed ceiling fans.

The start winding is placed 90 electrical degrees from the run winding. It is connected one circuit and is connected in series with the oil capacitor. Figure 1-175 is two schematics showing two ways that the start winding can be connected for operation. These connections can also be used on three-speed motors.

With connection (a), the start winding and the run winding always receive the same voltage. When a lower speed is selected, the starting torque will be substantially reduced. With connection (b), the line voltage is applied to the start winding on all speeds, giving the motor a better starting torque than connection (a) does. These motors are usually nonreversible. If they are reversible, the start-winding leads will be interchanged with respect to the run-winding leads, as with other capacitor motors.

5. Three-Speed, Single-Voltage, Permanent-Split Capacitor Motor. This motor is similar to the two-speed motor just described. The third speed is yet another winding inserted on top of the high- and second-speed windings. Like the second-speed winding, it is usually one circuit and must be of the same polarity as the poles with which it is wound. Figure 1-176 illustrates the three-speed winding, and Figure 1-177 shows another three-speed connection. The

wire size of the medium and low speed can be smaller than that of the high speed. Any single-speed permanent-split capacitor motor can be redesigned as a two-or more-speed motor by adding turns to the run winding, as described above.

The start winding for this motor has the same characteristics as the previously described permanent-split capacitor motors. The start winding will be connected across the high winding or across the line. Figure 1-175 illustrates both ways.

These schematic diagrams of the three-speed motor show the current flow when the motor is connected for the three different speeds. On high speed, shown in Figure 1-178, the high-run winding and the start winding are across the line. On medium speed, shown in Figure 1-179, the high-speed winding is in series with the medium-speed winding. The start winding is in parallel with the high-speed winding and in series with the medium-speed winding. In low speed, shown in Figure 1-180, both the medium-speed winding and the low-speed winding are in series with the high-speed winding. The start winding is in parallel with the high-speed winding and in series with the medium- and the low-speed windings. The start winding is sometimes connected so that it is always across the line, as shown in Figure 1-176. If there is no load on this motor and either medium or low speed is selected, the motor will run at high speed. It will run more quietly and draw less current than if the high speed is selected. With a load applied, there will be more slip, and the speed will be reduced.

Figure 1-181 shows a factory schematic of this motor; Figure 1-182 shows a six-pole, three-speed permanent-split capacitor-run motor; and Figure 1-183 is the slot layout of the motor in Figure 1-182.

TWO-VALUE CAPACITOR MOTOR

The two-value capacitor motor has an oil-filled capacitor connected in parallel with the electrolytic capacitor and the stationary switch contacts (see Figure 1-184). At start, both capacitors are in parallel with each other, but in series, with the start winding. This creates a high-starting torque, which is usually required by compressors, stokers, and so on. When the stationary switch contacts open, the electrolytic capacitor is eliminated from the start circuit. Current still flows in the start winding, but is limited by the low Mfd value of the oil-filled capacitor. The oil-filled capacitor will raise the power factor, reducing the magnetizing current supplied by the line. The power factor is explained in Chapter 3. Figure 1-185 is a simplified connection of a two-value capacitor motor. Both the run and start windings remain in the circuit at all times.

START-WINDING CONNECTIONS

The connections used with capacitor-start motors and two-value capacitor motors are sometimes hard to recognize because of the location of the capacitors. Some motors will have capacitors located in as many as three places on and in the motor. Regardless of the location, the following schematic diagrams illustrate

most of the start-winding connections. The schematic diagrams start with a one-voltage start winding with one electrolytic capacitor and proceed to the more complex combinations.

1. Single-voltage start winding with one electrolytic capacitor.
2. Single-voltage start winding with two electrolytic capacitors in parallel.
3. Two electrolytic capacitors connected in series.
4. Two electrolytic capacitors connected in series, in parallel with two electrolytic capacitors connected in series.
5. Two electrolytic capacitors connected in parallel, in series with two electrolytic capacitors connected in parallel.
6. Two-voltage start winding with one set of stationary switch contacts.
7. Two-voltage start winding with internally connected line leads.
8. Two-voltage start winding with two stationary switch contacts.
9. One-voltage start winding with a separate winding for an oil-filled capacitor.
10. One-voltage start winding with a potential relay.
11. Two-voltage start winding with one potential relay.

All start-winding connections using electrolytic capacitors can also be two-value capacitor connections. For this reason, the oil-filled capacitor connections will be included in all the diagrams but will be drawn with broken lines.

Oil-filled capacitors are always connected in parallel to the electrolytic capacitor(s) and the stationary switch contacts. If more than one oil-filled capacitor is used, they will be connected in parallel to each other. Oil-filled capacitors are never connected in series in any capacitor motor. The lead wire used for the oil-filled capacitor connections should be rated for at least 600 volts. The voltage across them will be much higher than the line voltage or the voltage applied to the start winding.

The oil-filled capacitors that are used in most two-value capacitor motors are rated for 330 to 370 volts; 440- and 660-volt capacitors are also available. The voltage rating of replacement capacitors should be the same as or higher than the original. The Mfd rating should be the same, as a higher Mfd value will allow more amperes through the start circuit and may cause the motor to overheat.

1. Single-Voltage Start Winding with One Electrolytic Capacitor. This winding may be designed for either high voltage or low voltage. Figure 1-186 shows the connection as it is used with a run winding designed for the same voltage. The capacitor's voltage rating should be the same as the voltage applied to the start winding. Figure 1-187 shows this connection when the start winding is designed for low voltage and is used with a run winding designed for high voltage. With this connection, the capacitor rating is for low voltage.

2. Single-Voltage Start Winding with Two Electrolytic Capacitors in Parallel. This connection is sometimes used when a large amount of capacitance is needed. It is also used if one capacitor is too large for the space available. This

connection is also used when it is necessary to increase the capacitor's cooling ability. Two capacitors in parallel, each rated as one-half the Mfd needed, have twice the cooling area that one large capacitor has.

The voltage rating of the capacitors used in this connection is the same as the voltage applied to the start winding. This connection is illustrated in Figure 1-188.

3. Two Electrolytic Capacitors Connected in Series. This connection is always used on high voltage (240 volts). The voltage rating of the capacitors used in this connection is always low voltage (125 volts). The capacitors should be of equal Mfd value. The voltage is divided across capacitors of unequal size in *inverse* proportion to their Mfd rating. If a capacitor of low value (150 Mfd) is connected in series with a capacitor with a larger value (270 Mfd), the voltage across the smaller capacitor will be high and cause early failure of the smaller capacitor. Figure 1-189 shows a series connection.

In most electrolytic capacitor connections it may be assumed that

1. All series capacitor connections are for high voltage.
2. The Mfd rating of all capacitors connected in series must be equal.
3. All capacitors connected in series are rated for low voltage.
4. No more than two electrolytic capacitors are ever connected in series.

4. Two Electrolytic Capacitors Connected in Series, in Parallel with Two Electrolytic Capacitors Connected in Series. Figure 1-190 shows this connection, which is used on large motors. It is always used on high voltage. All capacitors must have equal Mfd ratings and should be rated for low voltage.

5. Two Electrolytic Capacitors Connected in Parallel, in Series with Two Electrolytic Capacitors Connected in Parallel. Figure 1-191 shows this connection, which is also used on large motors and is always used on high voltage. All capacitors should have the same Mfd values and be rated for low voltage.

6. Two-Voltage Start Winding with One Set of Stationary Switch Contacts. Figure 1-192 shows this connection, which uses one or more electrolytic capacitors connected in series with each half of the start winding. If more than one capacitor is used in each half, they should be connected in parallel with each other, never in series. The electrolytic capacitors should be rated for low voltage, and the total capacitance for each half must be the same. Both sides of the stationary switch are brought out of the motor and labeled T_9 and T_{10}. Oil-filled capacitors are usually not used with this connection.

7. Two-Voltage Start Winding with Internally Connected Line Leads. Figure 1-193 shows that T_9 and T_{10} are internally connected to leads T_1 and T_4. The switch contacts are in series with the run-winding leads T_4 and T_{10}. This connec-

tion uses one or more electrolytic capacitors connected in series with each half of the winding. If more than one capacitor is used in each half, they should be connected in parallel. The capacitors are rated for low voltage, and the same Mfd values should be used in each half. Oil-filled capacitors are not used in this connection.

8. Two-Voltage Start Winding with Two Stationary Switch Contacts. Figure 1-194 shows this connection, in which there are two sets of stationary switch contacts that are internally connected in series with T_6 and T_8. If more than one electrolytic capacitor is used, the same rules apply as for a two-voltage start winding with one set of stationary switch contacts.

9. One-Voltage Start Winding with a Separate Winding for an Oil-Filled Capacitor. This connection, as shown in Figure 1-195, has a separate winding that is in parallel with the regular start winding. It is wound with smaller wire than is used in the regular start winding. This winding is connected internally to T_5 with the regular start winding. It is wound with the regular start-winding pole groups and is connected so that it has the same polarity as does the regular start-winding poles. The other end of this winding is connected in series with the oil-filled capacitor and T_8, as shown. If possible, the connection to T_8 should be made permanent and not accessible.

10. One-Voltage Start Winding with a Potential Relay. How the potential relay operates has already been explained. The oil-filled capacitor and the electrolytic capacitor should not be in the winding-relay circuit. The voltage rating of the relay must be the same as the voltage that is applied to the start winding. Figure 1-196 shows this connection with an oil-filled capacitor.

11. Two-Voltage Start Winding with One Potential Relay. The relay used for this connection is rated for low voltage (see Figure 1-197). The relay is connected in parallel with one section of the start winding. The contacts of the relay should have leads labeled T_9 and T_{10}. The explanation for a two-voltage start winding with one set of contacts applies to this connection. The potential relay can replace the centrifugal switch system of most capacitor-start motors.

CALCULATIONS FOR REWINDING AND RECONNECTING

Before making any rewinding or reconnecting calculations, you should understand wire size and its measurements. The size of copper magnet wire is designated by its diameter and identified by a gauge number. The diameter may be measured in thousands of an inch by a micrometer and its gauge number by means of an American Wire Gauge (A.W.G.).

Refer to Table I in the Appendix and note that the first column of this table for bare copper wire lists the various sizes of wire. The second column lists the diameter of each wire in inches. For size No. 18 in the first column, the diameter is 0.0403 in. The figure can be read as 40.3 thousands of an inch, or 40.3 mils, just by moving the decimal point three numerals to the right. A mil, therefore, is one thousandth (1/1000) of an inch.

As we are primarily interested in the safe ampere-carrying capacity of a wire, all computations involving round copper wire are based on a term called *circular mil area*. This area is arrived at by multiplying the diameter in mils by itself. In other words, the diameter squared is the circular mil area. Looking at column 3 in the table alongside No. 18 wire, we find the area in circular mils to be 1,624. This is found by multiplying 40.3 by 40.3, the diameter in mils squared.

From Table I we find that

1. The larger the gauge number, the smaller the wire; for example, No. 20 is smaller than No. 17. This is shown in the wire table. Number 20 wire has an area of approximately 1,000 c.m. (circular mils), whereas No. 17 has an area of 2,000 c.m.
2. By examining the wire table, it can be seen that the area in circular mils doubles or halves every three numbers. By adding three gauge numbers, the circular mil area is halved. By subtracting three gauge numbers, the circular mil area is doubled. Thus, No. 17 has twice the circular mil area as No. 20, and No. 18 has half the circular mil area of No. 15. Two No. 18 wires are the equivalent in area to one No. 15.
3. A No. 10 wire is approximately 100 mils in diameter and has approximately an area of 10,000 circular mils.
4. Every ten sizes the circular mil area is divided or multiplied by ten. For example, a No. 10 wire has a circular mil area ten times that of No. 20 wire. From this and the previous fact, the circular mil area of nearly all wires can be approximated.
5. Adding three wire sizes doubles the resistance. Subtracting three wire sizes halves the resistance.
6. Adding three wire sizes halves the weight of the wire. Subtracting three wire sizes doubles the weight of the wire.

Rewinding for a Change in Voltage

One of the simplest changes is a voltage change. The only change necessary for this type of conversion is in the wire size, the number of turns per coil, and, in some instances, a capacitor-value change. The coil span and connection are not changed.

RULE 1.

$$\text{New turns} = \frac{\text{new voltage}}{\text{orig. voltage}} \times \text{orig. turns}$$

RULE 2.

$$\text{New c.m. area} = \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}$$

RULE 3.

$$\text{New capacitance in } \mu f = \frac{(\text{orig. voltage})^2}{(\text{new voltage})^2} \times \text{orig. } \mu f$$

The following example will illustrate the above rules. A 115-volt, one-horsepower, 1,725-rpm, 60-cycle, capacitor-start motor having 36 slots is to be rewound for 230 volts, at the same speed. Find the new turns per coil, the wire size for both windings, and the capacitor μf.

DATA:

Run winding,	span 1–9	1–7	1–5	No. 15
	turns 38	26	20	
Start winding,	span 1–10	1–8	1–6	No. 19
	turns 14	28	15	

Use Rule 1 for the new turns. Because the new voltage is twice the original voltage, the turns per coil will be doubled.

Run winding, span 1–9	1–7	1–5
Run winding, new turns 76	52	40
Start winding, span 1–10	1–8	1–6
Start winding, new turns 28	56	30

Use Rule 2 for the new circular mil area.

$$\begin{aligned}\text{New c.m. area} &= \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}\\ &= \frac{115}{230} = \text{one-half c.m. area}\end{aligned}$$

R.W.:

c.m. area of No. 15	= 3,257 c.m.
one-half of 3,257	= 1,628
1,628 c.m.	= No. 18

S.W.:

c.m. of No. 19	= 1,288
one-half of 1,288	= 644 c.m.
644 c.m. area	= No. 22

Use Rule 3 to determine the size of the capacitor.

$$\text{New capacitance in } \mu\text{f} = \frac{(\text{orig. voltage})^2}{(\text{new voltage})^2} \times \text{orig. } \mu\text{f}$$

$$\text{New } \mu\text{f} = \frac{(115)^2}{(230)^2} \times 600\ \mu\text{f}$$

$$= \frac{13{,}225}{52{,}900} \times \mu\text{f} = \frac{1}{4} 600\ \mu\text{f}$$

Therefore the new capacity will be 25 percent of the original capacity. If the 115-volt motor had a 600-μf capacitor, the new capacitor needed for the 230-volt rewind would be 150-μf. Be sure to select a 230-volt capacitor for the replacement. The start winding need not be changed in a 115- to 230-volt conversion if the start winding is connected across half the run winding.

In this case, the run winding will also act as an autotransformer. Because the voltage across two poles of a four-pole run winding is one-half the line voltage and because the start winding is connected across two poles, the start winding will receive one-half the line voltage.

Assume that the above motor is to be rewound for dual-voltage operation on 115 or 230 volts. Proceed as follows:

1. Rewind the run winding as before for 230 volts. However, bring out six leads for a dual-voltage, externally reversible operation, as shown in Figure 1-131.
2. Use the same turns in the run winding as calculated in the previous example.
3. Because the start winding is connected to one section of the run winding, no change is necessary.
4. The two sections of the run winding are connected in series for 230 volts and in parallel for 115 volts.

Reconnecting for a Change in Voltage

The principle for all reconnections for voltage change is that the original pole voltage remains the same despite the line-voltage change. Thus, a four-pole, 230-volt, series-connected motor may be converted to operate on 115 volts merely by reconnecting it in two parallel or in two circuits, as shown in Figures 1-198 and 1-199. Note that in either connection, the voltage across each pole remains the same.

Voltage changes by means of reconnections are not always possible. For example, a four-pole, series-connected motor cannot be reconnected for a higher-voltage operation because if a higher voltage is impressed on the series connection, the voltage across each pole will be greater than they were designed for, and so they will burn out. Likewise, a two-pole, two-parallel motor cannot be reconnected for a lower voltage because there can be no more than two parallels in a two-pole motor.

Rewinding for a Change in Speed

Before devising specific rules for rewinding a capacitor-start motor for a change in speed, it is necessary to explain and define two terms essential to the calculations for this type of conversion. These terms are *effective turns* and *chord factor*. Effective turns in a coil are usually different from the actual turns in a coil. This is because the effective turns depend on the span of the coil. A full span will make the coil 100 percent effective. A lesser span will make the coil less effective. For example, a full-span coil having 20 actual turns will also have 20 effective turns, whereas a lesser-span coil of 20 turns may have only ten effective turns. In Figure 1-200, note that each pole of the run winding of this particular motor consists of four coils, each having different spans. From the above it can readily be seen that the outer coil will be more effective than the other coils because it has a greater span. The amount of effectiveness will depend on the number of electrical degrees spanned. Here, each pole covers a distance of 180 electrical degrees.

To compute the effectiveness of each pole, examine the four-pole, 36-slot motor of Figure 1-200. Each pole has nine slots, and because this is equivalent to 180 electrical degrees, it follows that there are 20 electrical degrees between the adjacent slots. The pitch of the outer coil in each pole is 1-9. The outer coil encompasses seven slots plus one-half slot for each of the slots it occupies. An easier way to determine this is to count the teeth encompassed by the coil that is being calculated. The number of teeth is used to find the angle of a coil. This formula can be used with any stator, regardless of the number of poles or slots.

$$\text{Poles} \times 180° \,/\, \text{number of teeth in stator} = \text{degrees per tooth}$$

$$\text{Degrees per tooth} \times \text{teeth encompassed by the coil} = \text{the angle of the coil}$$

$$\text{Sine of one-half the angle of the coil} = \text{chord factor}$$

Eight teeth are encompassed by a coil with a 1-9 span, and so the angle of the coil is

$$8 \times 20° = 160°$$

$$\text{One-half } 160° = 80°$$

$$\text{Sine of } 80° = 0.984, \text{ or the chord factor of the coil}$$

To find the number of effective turns of a coil, multiply the number of actual turns by the chord factor. Table VIII in the Appendix can be used to find the most common chord factors. A calculator with a sine function can also be used.

For the above motor, the chord factor of the outer coil is 0.984, and the number of effective turns is equal to the number of actual turns multiplied by 0.984. The next coil in the pole spans six slots and is equivalent to six times 20, or 120 electrical degrees. Its chord factor is 0.87, and the number of effective turns is equal to the number of actual turns in the coil multiplied by 0.87.

From the above, we obtain the following formula:

$$\text{Effective turns} = \text{actual turns} \times \text{chord factor}$$

To calculate the number of effective turns in one pole of a motor, we shall assume a four-pole, 36-slot motor, as in Figure 1-200. This motor has nine slots per pole and four coils in each pole of the run winding. Use chord factor from Table VIII in the Appendix.

Span	*Actual Turns*	*Chord Factor*		*Eff. Turns*
1–9	30	0.98	=	29
1–7	30	0.87	=	26
1–5	18	0.64	=	12
1–3	20	0.34	=	7
				74

The number of effective turns in the start winding can be found in exactly the same manner.

It was mentioned at the beginning of this section that it would be necessary to compute the number of effective turns for a conversion in speed.

As an example, assume that the four-pole, 36-slot, 1,750-rpm motor of Figure 1-200 is to be rewound for six poles, 1,150 rpm.

STEP 1. Compute the total number of effective turns in the entire run winding. For a four-pole motor, this is the number of effective turns for one pole multiplied by four, or 74 × 4 = 296 effective turns.

STEP 2. Rewinding for six poles:

$$\text{New eff. turns} = \frac{\text{orig. rpm}}{\text{new rpm}} \times \text{orig. eff. turns}$$

$$= \frac{1{,}800}{1{,}200} \times 296 = 444 \text{ turns for entire run winding}$$

STEP 3. Determine the number of effective turns per pole:

$$\text{Eff. turns per pole} = \frac{\text{total turns}}{\text{poles}} = \frac{444}{6} = 74 \text{ eff. turns}$$

Because this will be a six-pole motor, each pole will occupy six slots. Three coils per pole will be used having pitches 1-7, 1-5, and 1-3, as in the six-pole layout of Figure 1-201. Note that the outer coils of each pole overlap one another.

STEP 4. It has been found in practice that the number of actual turns are approximately 1.25 the number of effective turns. To obtain the number of actual turns from that of the effective turns, multiply by 1.25. This will be 74 × 1.25 = 92 actual turns.

STEP 5. Because the outer coils of adjacent poles overlap, use half the turns in coil 1-7, as for 1-5 pitch. Use the same turns for pitch 1-3.

Span	*Turns*	*Chord Factor*	*Eff. Turns*
1-7	23	1.0	23.0
1-5	46	0.87	40.0
1-3	23	0.50	11.5
	92		74.5

The sum 74.5 checks with 74 effective turns originally computed for each pole of this six-pole motor.

Compute the start winding in the same manner.

To determine the size wire necessary in this conversion, compute in the following manner:

$$\text{New c.m. area} = \frac{\text{new speed}}{\text{orig. speed}} \times \text{c.m. of orig. wire}$$

$$= \frac{1{,}200}{1{,}800} \times \text{c.m.} = \frac{2}{3}\,\text{c.m. of orig. wire}$$

If the original wire were No. 17 = 2,048 c.m., then

$$2/3 \times 2{,}048 = 1{,}365 \text{ c.m.}$$

$$1{,}365 = \text{No. } 19$$

It is important to take into consideration the centrifugal device in making a speed change. It is essential that the stationary switch open at the proper speed (approximately 75 percent of normal speed). Therefore, in changing, for exam-

ple, from a four-pole to a six-pole motor, it must be ascertained beforehand whether or not the centrifugal device will function at approximately 900 rpm.

CAPACITOR FAILURE

Capacitor failure can be contributed to one or more of the following reasons:

1. Excessive voltage.
2. Excessive-duty cycle.
3. Excessive temperature.
4. Internal corrosion.

Excessive Voltage

Excessive voltage will cause arcing through the oxide film or dielectric, resulting in a permanent short. One of the ways that excessive voltage can occur is when the start-switch contacts of the motor chatter before opening. This can subject the capacitor to voltages up to two or three times the rated voltage. This condition will also shorten the life of the contacts if not corrected.

When the motor is disconnected from the line and the start contacts close, the capacitor discharges into the start winding. This will result in a braking effect on the motor but will not harm the motor or capacitor. To minimize the braking effect and the extra stress on the start contacts, a 15,000-ohm resistor may be soldered across the capacitor's terminals.

Excessive-Duty Cycle

If the voltage does not exceed the capacitor rating but is applied for a longer period than recommended, the extra heat accumulated will dry out the moisture content of the electrolyte and char the paper, and the capacitor will cease to function. In this case, the failure is considered "burn up," and the capacitor may not be found to be short-circuited. It would likely test "open," as no electrolytic action can take place without moisture. This condition can also be caused by too many starts per hour. Sometimes the load requires more than the recommended starts per hour. In this case, the heat can be dissipated more efficiently by using two capacitors in parallel, each rated as one-half the original. This will double the heat-radiating surface and have the same Mfd rating.

An excessive-duty cycle also includes prolonged starts. An electrolytic capacitor should be in the circuit for no longer than three seconds. Taking too long to reach full speed can be caused by the following reasons:

1. Overload.
2. Worn bearings.
3. Wrong-sized capacitor.
4. Low voltage.

1. An overload can be corrected by reducing either the size of the pulley on the motor or the actual load. If neither can be reduced, a larger motor must be installed.

2. Worn bearings have the same effect as does an overload. The solution is to replace the bearings.

3. If the capacitor is too small, the amperes of the start winding will be reduced. The result is a reduced starting torque and a longer starting time. If the capacitor is too large, it will cause a braking effect at about 50 to 60 percent of full speed, preventing the start contacts from opening. The proper-sized capacitor can be determined from "The Right-sized Capacitor" in this chapter.

4. Low-line voltage will prolong the start time and can be caused by overloaded branch circuits or circuit wiring that is too small. In this case, it may be necessary to install another circuit for the motor.

Low-line voltage is also caused by loose connections. A loose connection becomes hot and eventually will char the wire and its insulation. Discolored wire at a connection is an indication that it is loose. The voltage drop is considered excessive when it stays below 5 percent of the motor's rated voltage while the motor is running.

Excessive Temperature

Capacitors operated above the maximum recommended temperature limit of 150° will have a shortened life expectancy. This is due to the increased evaporation rate of their water content. The arcing or puncture point of the oxide film or dialectric is lowered at high temperatures. The possibility of voltage failure increases as the temperature rises.

Internal Corrosion

Corrosion destroys the oxide film, causing quick failure because of a breakdown. It also eats away at the connection tabs, causing an open circuit. Clorides are particularly detrimental and can be traced to poor manufacturing or a broken or defective seal, permitting moisture absorption.

One of the more elusive malfunctions of capacitors occurs when the connecting strap between the plate and the terminal is broken. Good contact is not established, and the motor occasionally will not start. If the switch and the governing device are not found to be faulty, pry out the retainer ring and carefully lift out the round terminal board, as shown in Figure 1-202. If the strap is not broken, the capacitor can be reassembled.

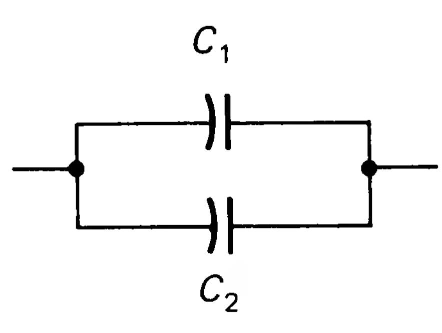
Some manufacturers place soft foam plastic on top of the capacitor terminals to secure and protect the wires. But when wet, the foam absorbs water and causes the terminals to arc and open at the rivets. The foam should be replaced with duct seal. The capacitors should always be securely fastened, or the movement will flex and break the lead wires.

THE RIGHT-SIZED CAPACITOR

One can do an acre of math trying to calculate the right-sized capacitor and still have to use some trial and error. A much easier way to do this is to combine the calculating and the trial and error. This method can be used to "custom fit" a capacitor to a motor at the site where it is used. Often the voltage and other conditions are quite different when the motor is used someplace other than at the service center. First, make available the capacitor leads and both sides of the start winding, as shown in Figure 1-203. Then apply power to both the start and run winding with the rotor locked.* The voltage across the capacitor and the start winding should be recorded. The voltage across the capacitor should be 10 percent higher than the voltage across the start winding when the right-sized capacitor is found. The voltage should be read as quickly as possible because the values will change as the windings get hot.

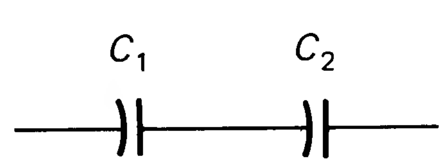
FORMULAS FOR FINDING CAPACITOR VALUES

Capacitors are connected in parallel, in series, and in a combination of both parallel and series. The formulas and connections are as follows:



1. Parallel. This connection can be made with any number of capacitors with any Mfd rating. The voltage rating of each capacitor must be the same as or higher than the voltage applied to the start-winding circuit. The total Mfd of capacitors connected in parallel is found by adding together the Mfd value of each of them.

$$C_1 + C_2 + C_3 = Ct$$



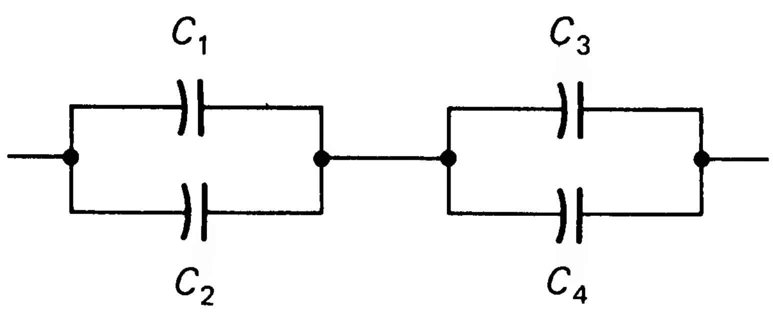
2. Series. This connection is usually found when the voltage applied to the start-winding circuit is 230 volts. In this case, the capacitors are rated as 125 volts. There are never more than two capacitors in series. Each capacitor should have the same Mfd rating. The total Mfd of equal Mfd capacitors in series is

*The rotor may be locked in a vise padded with wood.

found by dividing the Mfd value of one by the number of them (2). If the capacitors have unequal Mfd values, the total Mfd is found by using the formula

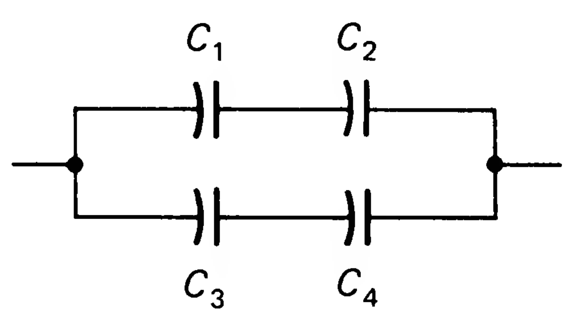
$$\text{Product} \div \text{sum } (C_1 \times C_2) \div (C_1 + C_2) = Ct$$

3. Two Capacitors in Parallel, in Series with Two Capacitors in Parallel.



The total Mfd of this connection is found by first adding the Mfd values of each parallel circuit and then using the proper series formula for the final total.

4. Two Capacitors in Series, in Parallel with Two Capacitors in Series.



The total Mfd for this circuit is found by using the proper formula to determine the Mfd in each series circuit. The final step is to add these totals together for the total Mfd.

TROUBLESHOOTING AND REPAIR

Defective capacitors are a frequent source of trouble in capacitor motors. They may short-circuit, open-circuit, or deteriorate with a resulting change in capacity. If they short-circuit, the motor windings may burn out. Poor starting or improper operation may result from an open-circuited capacitor or one that has a changed capacity.

The purpose of the capacitor is to make the start-winding current lead the current of the run winding by 90°. The right-sized capacitor for the motor will give the start winding this lead. If there is not enough capacitance, the currents will become less than 90° apart, and the rotating magnetic field will not have the maximum effect. The smaller a capacitor's Mfd value is, the less current will be available for the start winding. The result of these two effects is less starting efficiency and ability.

Although both electrolytic and oil capacitors are used on capacitor motors, the electrolytic capacitor is the one that more frequently fails. Both types can be tested with the following methods. All motor leads must be removed for these tests.

CHARGE-DISCHARGE TEST. Using line voltage with a 1,800 watt resistor in series with one lead, touch the terminals of the capacitor briefly to charge it, as shown in Figure 1-204. Then short-circuit the terminals with a screwdriver, as shown in Figure 1-205. A snappy spark should be visible. If the capacitor does not spark, charge and discharge it several times. If there is little or no sparking, the capacitor is either open or seriously diminished in capacity. If the test leads arc when touching the capacitor's terminals and there is no charging, the capacitor is shorted.

Caution. If line voltage is applied to a capacitor, it can explode. This can happen to a new capacitor as well as a defective one. Thus place a cardboard box or a pail over the capacitor being tested to prevent injury.

OHMMETER TEST. Place the test leads of an ohmmeter on the capacitor's terminals. If the capacitor is not faulty, the needle will peg zero and slowly return toward infinity. Reverse the test leads and test it again, and it will do the same thing. An infinity or near-infinity reading means that the capacitor is open. A continuous zero reading will mean that the capacitor is shorted. Neither the charge-discharge test nor the ohmmeter test will show the capacitor's true value, as it may have lost some of its capacitance because of the evaporation of the electrolyte but still pass these tests.

As a result of these tests, the capacitor is suspected of being defective and it should be replaced. If after replacement, the motor starts and has proper torque, it may be concluded that the capacitor was faulty. Several manufacturers have capacitor selectors that provide capacities ranging from 80 to 1000 μf, merely by changing a switching arrangement.

CAPACITY TEST. To determine a capacitor's strength, an ammeter, a voltmeter, and line voltage are needed. Place an ammeter in series with the capacitor and a voltmeter across it, as shown in Figure 1-206. Caution must be used in this test because line voltage is applied to the capacitor. When this is done, the capacitor can explode, and so place something over the capacitor, such as a cardboard box. The capacitor should be in the circuit for as short a time as possible.

From the meter readings, the capacitor's rating in microfarads can be obtained from the following formula:

$$\text{Capacity in } \mu\text{f} = \frac{159{,}300}{\text{frequency}} \times \frac{\text{amperes}}{\text{volts}}$$

If the formula is used on 60 cycles and 120 volts, it can be shortened to:

$$\frac{159{,}300}{60} = 2{,}655$$

$$\frac{2{,}655}{120} = 22$$

$$\text{Amperes} \times 22 = \mu\text{f}$$

For 120 volts the multiplier is 22, or amperes × 22 = Microfarads. And for 240 volts, 2,655/240 = 11, or amperes × 11 = Microfarads. If the capacity is 20 percent less than the stamped rating, replace it. For a given voltage, the Mfd needed will increase as the horsepower increases. An increase in Mfd will mean an increase in amperes available for the start winding.

The start circuit is more subject to problems than the run circuit is because it is designed to be energized for only one to three seconds. If it is energized any longer, both the winding and the capacitor will become overheated. The order in which the start-winding components break down are as follows: (1) switch contacts, (2) capacitor, (3) centrifugal device, and (4) windings. The switch contacts become burned and pitted after a great many starts. The capacitor will break down sooner than normal if it is in the circuit too long or if it is not given enough time to cool off between starts. Twenty starts per hour is considered maximum.

The centrifugal device will become worn and/or dirty, resulting in a malfunction. Usually the device will stick in the open position. The winding can become charred from being in the circuit too long. The heating and cooling of the winding contribute to insulation breakdown between the start and run windings. New motors have no insulation between the start and run windings. A layer of the right temperature class insulation between the two windings decreases the chance of a short. Several classes of tape are available for this purpose.

A capacitor start motor should jump up to top speed quickly when full voltage is applied at no load. The starting torque should lift one side of the motor off the bench on any T-frame motor. This snappy start will be noticeably reduced if the capacitor is too small. A capacitor that is too small will cause a more noticeable drop in torque because less Mfd will reduce the amount of current available to the start winding. A capacitor that is too large will have a braking effect when the motor approaches the speed at which the start winding is switched out of the circuit. When there is low-line voltage, this braking effect becomes even more pronounced. The result is that the motor cannot accelerate over 50 to 60 percent of full-load speed, and the start winding cannot switch out of the circuit. A low-voltage braking effect can be compensated for by using a smaller Mfd capacitor.

The failure to pull up to speed can also be caused by the centrifugal devices switching the start winding off too soon. Without the start winding in the circuit

at less than 50 percent of full speed, the run winding alone cannot pull the load up to speed. Weak springs on the centrifugal device will allow the contacts to open too quickly. The load will then slow down the motor until the contacts again close, energizing the start winding and speeding the motor up. The motor will continue to cycle like this until it either blows a fuse or burns out the motor. This same cycling effect will occur when a potential relay that is rated for a low voltage is used on high voltage. In this case the contacts will open very quickly, although the motor will start if there is no load. A current-operated starting relay that is rated for a larger motor than it is being used on will drop the contacts open too soon and also start to cycle underload. This premature shutdown of the start winding can be hard to detect when the motor is being tested without load. If this problem is suspected, the motor should be load tested before it is put back into service.

TWO-VALUE CAPACITOR MOTOR. The two-value capacitor motor starts in the same way as the capacitor-start motor does, but after the start winding is disconnected from the circuit, the oil capacitor, which is in parallel with the electrolytic capacitor and the start contacts, remains in the circuit. The oil capacitor has a low microfarad rating and can be in the circuit continuously. Its purpose is to correct the motor's power factor. Oil capacitors are always connected in parallel with the electrolytic capacitors and the start contacts. If there is more than one, they are connected in parallel with each other, never in series. Figure 1-207 is a connection using four oil-filled capacitors in parallel. Note that if the oil capacitor becomes shorted, the electrolytic capacitor and start switch will be bypassed, and the start winding will receive full voltage, as shown in Figure 1-208. If the motor were started with this condition, there would be very little starting torque because there would be no capacitors in the start-winding circuit.

In an emergency, the motor may be run without the oil capacitors, but it will lose some efficiency. The oil capacitor is sometimes called the run capacitor, but this is misleading, because it is then associated with the run winding. The purpose of the oil-filled capacitor is to correct the power factor. Correcting the power factor lowers the amperes of a circuit that has a large amount of inductive reactance. This condition is common in electric motors. When the amperes of a circuit are lowered, the circuit's voltage will increase. This will be explained in Chapter 3.

Using the Test Panel

The test panel shown in Figure 1-209 can be used in many ways. Its main function is to prevent damage to the components being tested, by limiting the current flow. The following list shows some of its uses:

1. Testing for opens.
2. Testing for shorts.
3. Testing for grounds.

4. Comparison test for identical circuits.
5. Locating reversed coils.
6. Testing capacitors.
7. Testing thermotrons.
8. Heating and softening windings.

1. Testing for Opens. Most of the testing with this panel can be done with 120 volts. When the test clips are shorted together and no switches are closed, the 240-volt light will light at half-brightness. The bulb is rated for 240 volts because when the test panel is used with this voltage, it will burn out a 120-volt bulb. The bulb will light if the circuit being tested is not open. If a start winding like that shown in Figure 1-210 indicates that it is open, it can be tested as follows· Disassemble the motor so that all components are accessible. Fasten one test clip to T_5 and touch the other to point D. If there is no light, the winding is open. If the coil connections are accessible, touch the test lead to points A, B, and C. If the open is between B and C, the light will light at point B but not at point C. The connections at points B and C should be examined, and if they are found to be good, the coil group between them will be open and will need to be repaired or replaced. If the connection splices are not accessible, a sharp point can be used to pierce the coil wire. (This method cannot be used on small wire.) Starting at the first group from T_5, test each coil group until there is no light. Proceed back, coil by coil, until the light again indicates a circuit. The open will be found between these two spots. If the windings are not open, touch the test clip to point E, and close the stationary switch contacts. If the contact points are dirty or badly pitted, the centrifugal device will not press them together hard enough to close the circuit. In this case the stationary switch contacts should be cleaned or replaced.

2. Testing for Shorts. Short together the test clips, and close the element switches one at a time. The ammeter will show an increase in amps for each switch. This amp reading should be noted beside each switch because it is this reading that will indicate a short in any device being tested. If a motor is not shorted, it will have some resistance to the flow of current. More element switches may then be closed and the motor started. The line-voltage switch should be closed only if the motor shows signs of being able to run. A large motor has much less resistance than does a small motor. If most of the motors being tested are above three horsepower, the number of resistors should be doubled.

Assuming that a shorted, dual-voltage capacitor-start motor, as illustrated in Figure 1-211, is being tested, the procedure is as follows: Connect the test leads to the motor lead wires. Close the test switches one at a time. The ammeter will indicate the same amps as when the test clips were shorted together and the brightness of the test light did not change. The amount of amps and the brightness on the test light both indicate a short, and the full-voltage switch should not be closed. Figure 1-211 shows three circuits in this motor. Separate the leads and

test the ones that light to one another individually. The circuits that are not shorted will have fewer amps than the shorted circuit does. Examine the short-circuited coil group to see whether it can be repaired or must be replaced.

*3. **Testing for Grounds.*** A motor is grounded when any of its circuitry makes electrical contact with the stator core, shell, end bells, or rotor. The motor illustrated in Figure 1-212 is grounded; the procedure for locating the ground is as follows: Separate the three circuits, fasten one test clip to the frame of the motor, and touch the other test clip to each of the three circuits. The circuit that is grounded will light the test light. The area of the ground can then be located. Disassemble the motor, and test for grounds as the end bolts and end bells are removed, as these are common places for grounds to occur when learning to rewind. If the ground is found to be in the stator, the general area of the ground can be located. Assuming that T_1 and T_2 are grounded, secure one test clip to the frame and the other to T_1. Close switches *1*, *2*, and *3* of the test panel and record the amp reading. Open the switches and move the test clip from T_1 to T_2. Close switches *1*, *2*, and *3* again and record the amps. The lead that records the highest amps will be closer to the ground. There are fewer turns of wire, and so there will be less resistance between this lead and the ground. The coils of wire between this lead and the ground will heat, and the coils beyond the ground will remain cool. These coils will be energized and will attract iron, such as a screwdriver. These two methods can be used to locate the general area of the ground.

*4. **Comparison Test for Identical Circuits.*** If there are no shorts in a motor such as that in Figure 1-213, T_1 and T_2 should have the same resistance as T_3 and T_4 do. If there is a short in one of the circuits, the shorted circuit can be found by applying current from several resistors to each of them and comparing the readings. The circuit with the short will have less resistance than the others and read more amps. This test can be used on any motor with identical circuits.

*5. **Locating Reversed Coils.*** A test rotor can be made with the rotor of a small motor. A rotor that is about one inch in diameter works very well. The rotor should spin freely and should be secured to a handle, as pictured in Figure 1-214. Both the start and run windings are energized for this test. Energize both windings with a reduced current, and move the rotor around the inside of the stator next to the slots. The rotor will spin until a reversed coil or group is found, and it will either stop or reverse itself. Low-voltage direct current can be applied to the windings and a small compass moved slowly around inside the stator to point out a reversed coil. The compass should reverse itself for each coil group as it is moved slowly around inside the stator.

*6. **Testing Capacitors.*** A capacitor can be tested safely by closing two switches and touching the capacitor's terminals. If the capacitor is shorted, the ammeter will show shorted amps. Touch together the test clips, and the reading will be the same as when the shorted capacitor is energized. If the capacitor is not shorted,

remove the test clips and short out the capacitor's terminals with a screwdriver, as shown in Figure 1-205. There should be a snappy spark. Full voltage can then be applied briefly and the amperes recorded. This reading with the proper multiplier can be used to find the capacitor's microfarad rating as explained on page 55 in "Capacity Test."

Caution. Capacitors can explode when full voltage is applied to them.

7. ***Testing Thermotrons.*** Thermotrons can be tested by applying current to P_1 and P_3. Apply 250 to 300 percent of the motor nameplate amp rating to the thermotron. The circuit will open after a short time, signifying that the contacts of the thermotron are not fused together. No circuit between P_2 and P_3 means that the heater is open and so the device should be replaced.

8. ***Heating and Softening Windings.*** If a winding has to be reshaped after it has been dipped in varnish and baked, it should be heated until it becomes soft. Connect the run winding to the test panel, and apply enough current to heat the windings slowly. Too much current can char the windings, and so it is important to watch the windings closely.

Defective Windings

Windings should be tested for (1) grounds, (2) open circuits, (3) shorts, and (4) reverses after rewinding. These are the four most common mistakes when rewinding. They can usually be found and repaired without doing over the rewind. After a motor has been in service for a reasonable length of time (a year or more), it is necessary only to determine that the winding is open, shorted, or grounded. The procedure then is either to rewind the entire windings or to replace the motor. Only rarely does it pay to spend any time isolating or repairing these problems in a motor that has been in service for very long. The test panel shown in Figure 1-209 can be useful in locating these problems.

Grounds. A winding is said to be grounded when it makes an electrical contact with the iron of the motor. Grounds may be caused by a number of conditions, the most common of which are the following: (1) the bolts that fasten the end plates to the frame may make contact with the winding as a result of the coils of the winding protruding too far from the ends of the slots; (2) the wires press against the laminations at the corners of the slots, which is likely to occur if the slot insulation shifts during the winding process or if the insulation tears during winding; and (3) the stationary switch may be grounded to the end plate.

To determine whether the winding is grounded, a test lamp may be used. One test lead to the lamp is connected to the winding and the other lead to the stator core or motor frame, as shown in Figure 1-215. If the lamp lights, the winding is grounded.

Should the winding prove to be grounded, try first to locate the ground by visual inspection; in other words, examine the winding closely to see whether any wires are touching the core. Try moving the turns of the winding back and forth while the test leads are connected to see whether the light flickers. A flicker under these conditions indicates that the grounded point has been temporarily removed, and usually a spark may be observed at the point of the ground.

If this test does not disclose the ground, it will be necessary to disconnect the splices between the poles and test each pole. After the poles have been disconnected, test each one individually, as described above, until the fault is found. When the grounded pole is located, determine the point of the ground and remove it by reinsulating or by rewinding. It may be necessary to remove the entire pole and rewind it more carefully.

Open Circuits. The usual cause of an open circuit in a capacitor-start motor is a loose or dirty connection or broken wire, which may be in the run winding, the start winding, the stationary switch, or the capacitor circuit.

To determine whether the run winding is open, the leads of the test lamp are connected to the ends of the winding, as shown in Figure 1-216. If the lamp lights, the circuit is complete. If the lamp does not light, an open circuit is indicated, as illustrated in Figure 1-217. The open circuit may be located by connecting one test lead of the lamp to one end of the winding and placing the other lead to the end of each pole separately, as indicated by points *1*, *2*, *3*, and *4* in Figure 1-218. If the lamp does not light at point *1*, the coil of the first pole is open. If the lamp lights at point *1* but does not light at point *2*, the second coil is at fault. If it lights at *1* and *2* but not at *3*, the third coil is at fault. Such a condition is shown in Figure 1-218. Note that the lamp also does not light at point *4*. After repairing the open circuit of coil *3*, the lamp should light at point *4*. If it does not light, coil *4* is also open and requires repair. By continuing in this manner the open circuit can be found.

An open circuit in the start winding may be difficult to locate, as not only is the winding itself involved but also the stationary switch and capacitor. The stationary switch is probably the worst offender in producing open circuits. The parts become worn, defective, and dirty; also, insufficient pressure of the rotating device against the stationary switch will prevent the contacts from closing and thereby produce an open circuit. Detailed tests for the capacitor can be found on page 55.

If the start winding is connected to the stationary switch and the motor is disassembled, the tests for an open circuit are as follows: The test leads of the lamp are connected to the leads of the start-winding circuit. The lamp should not light until the two contacts of the stationary switch are pressed together. If the lamp does not light, the open may be in either the switch or the winding. By next connecting the test lamp directly across the winding, it can be determined whether this is at fault. If it is not, the trouble is in the switch, which should then be examined carefully, all contacts cleaned, and the pressure of the centrifugal device adjusted.

If the motor has been assembled and the start-winding is to be tested for an open circuit, connect the test leads of the lamp to the start-winding circuit, as shown in Figure 1-219. The lamp should light, but if it does not, it is possible that the stationary switch contacts are not closed. The rotor is then pushed lengthwise toward the front end. This may cause the contacts to close; if so, the lamp will light. To correct this trouble, add several fiber washers to the pulley end of the rotor shaft to keep the rotor pushed forward. It may be necessary to remove washers from the front end to accomplish this. In all cases be certain that the rotor core is aligned with the stator core.

If tests show that the trouble is not in the stationary switch, then the open circuit is in the start winding. If this is true, the start winding must be tested and repaired in the manner described for the run winding.

Shorts. Two or more turns that contact each other electrically will cause a short circuit. This condition may develop in a new winding if the winding is tight and much pounding is necessary to place the wires in position. In other cases, excessive heat developed from overloads will make the insulation defective and will cause shorts. Usually a short circuit exists when the winding smokes while the motor is running or when it draws excessive current at no load.

Several methods may be employed in general practice to find shorted coils in a motor. Among these are the following:

1. Run the motor for a short time and then locate the hottest coil by feeling the poles. This coil is generally the one that is shorted.
2. Use an internal growler. The growler is a coil of wire wound on a laminated iron core and connected to a 115-volt ac outlet. After the motor is disassembled, the growler is placed on the core of the stator and moved from slot to slot. A shorted coil will be indicated by the rapid vibration of a metal blade, such as a hacksaw blade, held at the other end of the coil, as illustrated in Figures 1-220a and b.
3. Use the voltage-drop test. The winding is connected to a source of low dc voltage, and a voltage reading is taken across each pole. The pole that has the least voltage drop is the shorted coil.
4. Use the strength-of-field test. A piece of iron is held against the core of each pole while the current from a low dc source is applied.
5. Use the ammeter. This method can be used on a two-voltage motor without disassembling it. The test panel is used for this. Connect T_1 and T_2 to the test clips, apply two resistors, read the amperes, and record them. Do the same with T_3 and T_4. Compare the two readings; the higher will be the shorted one. This comparison test can also be used on individual coils.
6. See whether there is a misalignment. When the iron of the rotor and the iron of the stator are misaligned, the motor will draw more current than it should and appear shorted. This can happen if the motor is not assembled properly: the core may slip in the shell of the stator, or the rotor may have slipped on the shaft.

Reverses. Reverses result from wrong connections between poles and are best discovered by means of a polarity test. Two methods are used, namely, the compass method and the nail method.

In using the compass method, the stator is placed in a horizontal position, and a low dc voltage is applied to the winding. The compass is then held inside the stator and moved slowly from one pole to another. The compass needle will reverse itself at each pole, as shown in Figure 1-221, if the winding is correctly connected. If the same end of the needle is attracted to two adjacent poles, a reverse pole is indicated.

In using the nail method, the stator is placed on its side, and a low voltage of either alternating or direct current is applied to the winding. A nail is placed on the core so that it extends from the center of one pole to the center of the next pole. If the adjacent polarity is correct, the nail will be attracted to both poles; but if the polarity is incorrect, one end of the nail will be repelled from its pole.

Should it be found that one pole has the wrong polarity, this error can be corrected by reversing the two lead connections to this pole. In the event that more than one pole has the wrong polarity, reference should be made again to Figure 1-100, and the poles connected as shown therein.

Repairs

We shall now consider the various troubles that develop in capacitor-start and split-phase motors and explain how they may be repaired. These troubles and their remedies will be grouped into four classes: (1) motor fails to start; (2) motor runs at a slower-than-normal speed; (3) motor runs very hot; and (4) motor runs noisily.

Motor Fails to Start. Failure of the motor to start when it is connected to a power line of the correct voltage may be due to (1) open run winding, (2) open start winding, (3) grounded winding, (4) burned or shorted winding, (5) open-circuited overload device, (6) excessive overload, (7) worn or tight sleeve bearings or defective ball bearings, (8) end plates improperly mounted, or (9) bent rotor shaft.

1. Open Run Winding. An open run winding may be discovered by testing the winding with a test lamp. If the lamp fails to light, the winding has an open circuit. The exact location of the open is determined by the method previously explained under "Open Circuits" and repaired by rewinding if necessary.

2. Open Start Winding. Three practical tests show whether the start winding has an open circuit. One method is to connect the motor to the power line. An open circuit in the start winding will cause the motor to hum, because only the run winding is in the circuit.

A second test is to turn the rotor manually. This may be done by winding a cord around the rotor shaft, as in Figure 1-222, and pulling the cord so that the rotor turns. While the rotor is thus turning, the power-line switch is turned on. If the motor continues to run, the trouble is in the start-winding circuit. Use caution with this method, as the string may catch and whip.

The third test for discovering an open circuit in the start winding is to use the test lamp. If the circuit is found to be open, the trouble is in the stationary switch, the start winding, or the capacitor.

The stationary switch should be examined first, as it is most likely to be the cause of the trouble. Moving the rotor shaft toward the front end plate may close the contacts of the switch, in case the trouble is at this point, and cause a test lamp in the circuit to light. The rotor may also have too much end play, which can be determined by moving it back and forth. There should be a maximum end play of not more than 1/64 in. If more end play is observed, fiber washers should be put on the shaft so that the rotor core lines up with the stator core. If too much end play is allowed, the rotor may come to a stop in such a position that the stationary switch contacts will remain open. If these tests have been made and the circuit still remains open, the motor should be disassembled and a test lamp used to check the operation of the switch. If found to be defective, the stationary switch should be carefully cleaned and all parts adjusted.

The start winding is next tested, if the stationary switch is found to be in good order. The flexible leads to the power line that are spliced to the wires of the coils are examined first and replaced if they are at fault. If the start winding is defective, the open may be located by the method described earlier in this chapter for open circuits. Although the break in the coil may be repaired by splicing if it is readily accessible, rewinding is necessary if the coil is burned or otherwise severely damaged. Should it be necessary to rewind the start winding, it is advisable to test the run winding thoroughly for any defects before replacing the new start winding over it.

3. Grounded Winding. One ground in a motor may not be noticeable in its running conditions, but two or more grounds in a winding are equivalent to a short circuit. This may cause a fuse to blow, or it may cause the winding to smoke, depending on the extent of the grounds. The ground can be located using the test panel and a screwdriver. After the motor is disassembled, fasten one test clip to the frame of the stator and the other to one lead of the grounded winding. Apply a limited amount of current, and move the metal blade of the screwdriver around the inside of the stator. The coils between the lead and the ground will be energized and will attract the iron of the screwdriver. The coils that do not attract the iron will be past the ground. The comparison test can be made by recording the amperes of one lead to the ground and the other lead of the grounded circuit to the ground. The lead with the higher amp reading will be closer to the ground. The connections can then be opened, the coil isolated, and the ground removed. A grounded winding may cause a shock if touched and is therefore dangerous. It is recommended that the motor frames be grounded under certain conditions.

4. Burned or Shorted Winding. A burned or short-circuited winding usually causes a fuse to be blown when the motor is connected to the line. If the fuse does not blow, the winding will smoke. In either event the motor must be disas-

sembled. A burned winding is easily recognized by its smell and its burned appearance. The only remedy is to rewind the motor completely or to replace it. Partial rewinding is recommended only for newly wound motors. If the winding is not burned and there is only a short circuit, the short may be located and repaired, as explained earlier in this chapter.

5. OPEN-CIRCUITED OVERLOAD DEVICE. Some motors are equipped with an overload device consisting of a bimetal element that will expand when heated and cause the associated contacts to open. This device is connected in series with the motor, as shown in Figure 1-223, and its contacts will open if the motor is overloaded or if for any other reason too much current flows through the winding. However, the contacts must close after the motor has cooled somewhat or when the overload is withdrawn. The contacts should be examined for dirty, defective, or burned points. If the points are in bad condition, the device should be replaced.

6. EXCESSIVE OVERLOAD. When too much load is placed on a motor not having an overload device, the motor will hum and stall. An overload condition may be readily determined by connecting an ammeter in the circuit, as shown in Figure 1-224, and noticing whether the ammeter registers a higher current reading than the ones recorded on the motor's nameplate. A snap-around volt ammeter-ohmmeter can be used for this reading. This instrument is shown in Chapter 3, Figure 3-185. A shorted winding will likewise cause a large reading. It is assumed, however, that previous tests have shown that the windings are neither shorted nor grounded.

7. WORN OR TIGHT SLEEVE BEARINGS. Bearing troubles frequently develop in motors after they have been in use for a considerable time. A worn sleeve bearing may be discovered by attempting to move the shaft up and down by hand, in the manner illustrated in Figure 1-225. If the shaft moves, it indicates a worn bearing or possibly a worn rotor shaft, as shown in Figure 1-226. In either event, new bearings are required. A small amount of play in the bearings will allow the rotor to touch the stator, as shown in Figure 1-227 and thus prevent the motor from starting. Quite often, sludge will accumulate in the worn part of the bearing and may prevent an up-and-down motion of the shaft. In this case the motor is disassembled so that the rotor is resting in one end plate. If the end plate can be wobbled back and forth, the bearing or shaft is worn.

A sleeve bearing is removed by placing a piece of round stock on the bearing in the end-plate housing and pressing it out by means of an arbor or some other type of press. A convenient tool for this purpose is a piece of round stock that has been turned down in a lathe to fit different sizes of bearings, as shown in Figure 1-228. Care should be exercised to press out the old bearing through the side of the end plate having the larger opening and to remove any screws or oil wick that may prevent the bearing from coming out easily.

The new sleeve bearing is set in place by using the round stock as before and pressing the bearing into the end plate. The bearing is pressed in to the proper distance from the side of the end plate having the larger opening. The oil holes must be lined up with those in the end plates, and the bearing must not be burred while being replaced.

New sleeve bearings are usually made a few thousandths of an inch too small and need to be reamed to the proper size. This is done by placing the end plates on the stator after the new bearings have been pressed in, but before the rotor is replaced, and using a through reamer to ream the holes. The reamer is first passed through the bearing in one end plate and then continued through the stator to the other end plate. In this manner, the bearings are reamed to the same size and also properly aligned. Separate reamers of the proper sizes will need to be used, however, when the rotor shaft requires different-sized bearings at the two ends. In such cases, care must be exercised to align the bearings correctly.

If the shaft is worn, it may be reconditioned to its original roundness and smoothness by turning it in a lathe. Then it must be fitted with a smaller-sized new bearing. Or, the shaft may be built up to its original size by forcing molten metal on it, in a process called *metallizing*. If this process is used, the metallized shaft is turned in a lathe to the correct size, and a standard-sized bearing is used to replace the old one.

When a bearing is allowed to become dry from lack of oil, the motor shaft may heat and expand to such a degree that it welds itself to the bearing. Such a condition is known as a *frozen* bearing. To repair a frozen bearing, the end plate and bearing must be knocked loose from the shaft or loosened with a blow torch. The shaft is then smoothed up, and a new bearing is installed. Ball bearings will be explained in Chapter 3.

8. End Plates Improperly Mounted. When an end plate is not fastened securely around the entire edge, as shown in Figure 1-229, the bearings are out of alignment, and the rotor can be turned by hand only with difficulty or not at all. The end plate should sound "solid" when tapped gently with a mallet or lead hammer and should fit the stator perfectly at all points. If it does not fit, all screws should be loosened and each one tightened a little at a time, thus drawing the plate evenly and securely to the stator. In assembling a motor, do not tighten the first screw on the end plate, then the next adjacent one, and so on. If tightened this way, the opposite side of the end plate will not contact the stator tightly.

9. Bent Rotor Shaft. A bent shaft, shown in Figure 1-230, may be suspected if the rotor does not turn easily by hand after it has been determined that the end plates are on properly. To determine whether the shaft is bent, the rotor is removed from the motor and placed in a lathe. With the lathe turning slowly, it is usually possible to see the rotor bobbing up and down if the shaft is bent. To locate the bend, a special gauge made for this purpose is held close to the shaft

while it is rotating in the lathe. If no such gauge is available, a piece of chalk can be held near the shaft. The bend portion of the shaft will touch the chalk during rotation and thus be marked.

A bent shaft may be repaired by securely mounting the rotor between centers in a lathe. A pry bar or a long section of pipe is inserted under the bent portion to obtain the necessary leverage. The pressure exerted in bending the shaft back into position must be carefully controlled. Usually, the bending should be done a little at a time, until the shaft is straight. This method should be employed only for small rotors; otherwise, the lathe centers may be damaged.

Motor Runs at a Slower-Than-Normal Speed. A motor that does not attain normal running speed is likely to have one or more of the following defects: (1) short circuit in the run winding, (2) start winding remaining in circuit, (3) reversed run winding poles, (4) other incorrect stator connections, (5) worn bearings, or (6) open rotor bars or end rings.

1. SHORT CIRCUIT IN THE RUN WINDING. A short circuit in the run winding will cause the motor to run at a lower speed than that for which it is rated and will produce a humming or growling noise. The pole that contains the short, as shown in Figure 1-231, will usually become excessively hot; it may also smoke if the motor is allowed to run for many minutes.

To locate the shorted pole, an internal growler is used. Or the pole may be located by merely feeling for the hot coil. The remedy for a short-circuited coil is to find the short and, after it is found, to insulate it if possible. If it cannot be insulated, rewind the coil or the entire winding.

2. START WINDING REMAINING IN THE CIRCUIT. The symptoms of this defect are the same as those for a shorted run winding. To determine conclusively that the start winding remains in the circuit, disconnect one lead of this winding and start the motor manually, as illustrated in Figure 1-222, and connect the power line after the rotor is turning. If the motor then runs properly, the stationary switch does not disconnect the start winding at the proper time.

The contact points of the stationary switch may be welded or stuck together; other faulty parts may be causing the contact points to remain closed; or the rotating device may not release the contacts on the stationary part because fiber washers are improperly placed on the rotor shaft. In any of these cases, the switch is repaired, as previously explained; a new switch is installed; or fiber washers are placed on the rotor shaft so that the switch will open and close in the proper manner.

3. REVERSED RUN WINDING POLES. If the poles are connected in such manner as to produce incorrect polarity, the motor will rotate slowly, if at all, and rotation will be accompanied by a growling noise. More definite analysis requires that the motor be disassembled and each pole tested for correct polarity by

the compass or nail tests previously described. When the pole of improper polarity is located, the lead wires of the pole are disconnected, reversed, and reconnected.

4. Other Incorrect Stator Connections. Incorrect connections between the poles of either the run or start winding may cause induced currents to flow in the pole coils, with the result that the coils will become overheated, smoke, and perhaps burn out. When this condition exists, the motor must be disassembled and the connections carefully remade, as explained earlier in this chapter under "Connecting Procedure." The amateur repairperson often makes mistakes in connecting the windings of this type of motor, one of the most common being that he or she connects two of the poles in series and the remainder in a closed circuit, in the manner shown in Figure 1-232. Extreme care should be exercised to connect all the poles exactly as required by the data.

5. Worn Bearings. A motor with worn bearings or worn shaft is noisy in operation and sluggish in rotation. The cause is that the rotor rubs against the stator while running, as shown in Figure 1-227. A worn bearing or worn shaft diagnosis may be confirmed by noting whether the shaft can be moved up and down while the motor is still assembled. In either case, repair should be made as explained earlier in this chapter.

6. Open Rotor Bars or End Rings. This problem occurs in larger capacitor-start motors. When a short or ground occurs in the slot near the rotor, an arc will form, and the heat will be directed at the rotor. This extreme heat will melt the rotor bar and cause it to open. When one or more rotor bars are open, the motor will lose power. This problem may not be detected until a load is applied. One symptom of open rotor bars is a lower-than-normal ampere reading when the motor is running with no load.

There are two methods of detecting an open rotor if the problem is not visible. Place the rotor in a growler, as pictured in Figure 1-233. Limit the current to the growler with a resistor, and place an ammeter in series with it. As the rotor is turned in the growler, the amps will be much lower as the open bar passes through the magnetic field of the growler. Another method that can pinpoint the open bar is done with a sheet of paper, some iron filings, and the growler. Place the rotor in the growler, and hold the paper containing the iron filings against the rotor. Turn the rotor slowly, and the filings will be attracted to the good bars but not the open bars. This test should be carried out before the stator is rewound. The cost of having the rotor bars recast or replaced will likely dictate replacement of the whole motor.

Motor Runs Hot. A motor may become excessively hot after running a short time for one of the following reasons: (1) shorted winding, (2) grounded winding, (3) short circuit between the run and the start windings, (4) worn bearings, or (5) overloading.

1. Shorted Winding. If either the run or the start winding has a short circuit, the shorted pole will become excessively hot when the motor is running. In addition, the motor operates with a growling noise. The winding will eventually become so hot that the entire motor will be damaged if it is allowed to run in this condition. The procedure for determining whether a short circuit exists and for locating it was explained earlier.

Unless the short, after having been located, can be repaired and insulated, the pole or the entire winding must be rewound.

2. Grounded Winding. A winding grounded in two or more places is equivalent to a shorted winding and will cause the motor to run very hot and will eventually produce severe damage. The grounded points are located by methods previously explained and are repaired by reinsulating, if possible. If reinsulating is impossible or seems inadvisable, the motor must be rewound.

Should the motor be grounded at one point only, it is likely that a shock will be felt if the motor is touched when running. This condition is dangerous, and therefore immediate repair is essential.

3. Short Circuit between the Run and the Start Winding. A short circuit between these two windings will permit a current to flow through a part of the start winding continuously while the motor is in operation and in time will burn out the start winding. To locate the shorted point, the windings are disconnected from the terminals; one of the leads of a test lamp (connected to the line) is connected to the run winding; and the other lead is connected to the start winding. The lamp will light, as the current flows from the run winding through the shorted point to the start winding. The start winding is then moved away from the run winding at various places in the stator. If the shorted point is moved, the lamp will flicker or go out. If the shorted point cannot be determined in this manner, a limited-current method can be used. After applying the current to one start lead and one run lead, the start-winding coils between the lead and the short should heat. The start coils beyond the short will not heat. If a difference in heat cannot be detected, compare the amperes between one of the run leads and each of the start leads. The start lead with the higher amp reading will be closer to the short. If the shorted point cannot be determined in this manner, it will be necessary to remove the coils of the start winding one at a time until it is located.

The short circuit can usually be repaired by inserting a strip of insulation paper in the slot between the two windings.

4. Worn Bearings. When the bearings are worn sufficiently to permit the rotor to touch the stator, the motor will become overheated after running for a short time. Worn bearings may be readily detected by trying to move the rotor shaft up and down while the motor is assembled. If such movement is possible, the bearings are worn. If the rotor is removed from the motor and found to have polished surfaces on it, this is an indication that the rotor is probably rubbing against the stator. This condition is repaired by replacing the bearings.

5. Overload. An overload on the motor will cause it to draw more than the rated current and thereby produce excessive heat. An ammeter is placed in the circuit to test for overload. Should the meter show a larger reading than that listed on the motor's nameplate, the load should be reduced or the motor replaced with a larger one. This test assumes that the motor is externally overloaded.

Motor Runs Noisily. There are several reasons that a motor may operate with an unusual amount of noise. The most common of these are (1) shorted winding, (2) improperly connected poles, (3) worn bearing, (4) worn stationary switch, (5) too much end play, and (6) foreign material in the motor.

The first three conditions all will produce a magnetic hum when the motor is running. When such a hum is noticeable, the repair person can be certain that one of these defects exists. More positive tests for locating these troubles and the methods of repairing them have already been explained.

Bearings that are excessively worn allow the rotor to rub against the stator when the motor is running and thus produce a loud noise. Specific tests for this trouble and repairs should be made in the manner already described.

A worn rotating device is likely to cause a noticeable noise when the motor is in operation. Because part of the switch is located on the rotor, in revolves at high speed. A loose member of the rotating device may hit or rub against some other part of the motor and thus make the noise. When such a defect is suspected, the rotor should be removed from the stator and the device fully inspected. It may be found that the faulty parts can be repaired; if not, a new device must be installed.

Should the rotor have an end play of more than 1/64 inch, it may produce a noise during operation. The remedy for this trouble is to place fiber washers on the rotor shaft at the proper places.

Sometimes foreign material, such as a piece of insulation or wire, becomes embedded in a winding or a slot and protrudes sufficiently for the rotor to rub against it. This will cause an undesirable noise. The foreign material can be located by dismantling the motor and inspecting all windings and slots carefully. After it is found, the foreign matter usually can be removed with a pair of pliers or a screwdriver. In removing it, care must be exercised not to damage the insulation on the wires or between the windings.

Figure 1-234 shows connection diagrams of single- and dual-voltage split-phase motors and single- and two-speed split-phase motors. These motors and line-wiring diagrams are the type received from motor manufacturers when a request is made for the connection diagrams for specific motors. Figure 1-235 shows a variety of connection diagrams of capacitor motors and are reproduced with permission of the motor manufacturers. Figures 1-236, 1-237, and 1-238 are two-pole diagrams.

Chapter 2

REPULSION-TYPE MOTORS

Repulsion-type motors are among the oldest forms of single-phase induction motors and were widely used from the 1930s through the 1950s. At least one manufacturer is still producing them today, but they have been largely replaced by split-phase and capacitor-start motors. When compared with the split-phase and the capacitor-start motor, the repulsion-type motor is much more efficient when starting a load, as it has a minimum amount of inrush, or starting, current. This gives it the capability of doing well on low-voltage conditions. Many of these older motors are still in use.

In general, repulsion motors may be divided into three classifications: (1) the repulsion motor, (2) the repulsion-start induction motor, and (3) the repulsion-induction motor. These motors are called *single-phase wound-rotor motors* and are defined and classified by NEMA as follows:

Repulsion Motor. A repulsion motor is a single-phase motor that has a stator winding arranged for connection to a source of power and a rotor winding connected to a commutator. Brushes on the commutator are short-circuited and are so placed that the magnetic axis of the rotor winding is inclined toward the magnetic axis of the stator winding. This type of motor has a varying-speed characteristic.

Repulsion-Start Induction Motor. A repulsion-start induction motor is a single-phase motor having the same windings as a repulsion motor, but at a predetermined speed, the rotor winding is short-circuited or otherwise connected to give the equivalent of a squirrel-cage winding. This type of motor starts as a repulsion motor but operates as an induction motor with constant-speed characteristics.

Repulsion-Induction Motor. A repulsion-induction motor is a form of repulsion motor that has a squirrel-cage winding in the rotor in addition to the repulsion-motor winding. A motor of this type may have either a constant-speed or a varying-speed characteristic.

These three classes are often confused by the beginner because of the similarity of names. But each is different from the others, having its own characteristics

and applications. However, one feature common to all is that each has a rotor containing a winding that is connected to a commutator. Figure 2-1 shows a repulsion-start induction motor. These motors generally operate from a single-phase lighting or power circuit, depending on the size of the motor.

CONSTRUCTION

Most repulsion-type motors generally consist of the following parts:

1. A stator similar to that of the split-phase or capacitor motor and one winding, usually of two sections, similar to the running winding of a dual-voltage split-phase, or capacitor motor. Figure 2-2 shows the stator of a repulsion-start induction motor.
2. A rotor having a slotted core into which a winding is placed and connected to a commutator. The rotor is similar in construction to the armature of a dc motor and will henceforth be referred to, interchangeably, as the rotor or armature. The slots are generally skewed to produce the same starting torque, regardless of the position of the armature, and to reduce magnetic hum. Figure 2-3 illustrates the armature of a repulsion-induction motor.

   The commutator may be one of two types: an axial commutator, with bars parallel to the shaft (Figure 2-3), or a radial commutator, with bars perpendicular to the shaft (Figures 2-4 and 2-5).
3. Two end plates or brackets that support the bearing in which the armature shaft must turn.
4. Brushes made of carbon that fit in the brush holders. The brushes ride against the commutator and are used to conduct current through the armature winding.
5. Brush holders, supported either on the front end plate or on the armature shaft, depending on the particular type of motor.

THE REPULSION-START INDUCTION MOTOR

The repulsion-start induction motor is a single-phase motor ranging in size from approximately one-quarter to ten hp. It has a high starting torque and a constant-speed characteristic. It is used in commercial refrigerators, compressors, pumps, and other applications requiring a high starting torque.

Repulsion-start induction motors are of two different designs. In one, known as the *brush-lifting* type, the brushes are automatically moved away from the commutator when the motor reaches approximately 75 percent of full speed. This type generally has the radial or vertical form of commutator (Figures 2-5 and 2-24). In the other, called the *brush-riding* type, the brushes ride on the commutator at all times. This type has the axial form of commutator, as shown in Figure 2-3. In other operating principles, these motor types are identical.

Operation of the Brush-lifting, Repulsion-Start Induction Motor

To produce a reasonably high starting torque in the repulsion-start induction motor, a winding is placed on the armature. When the winding on the stator is excited by current supplied from the line, a flux is set up that induces current in the armature winding. The poles formed on the stator and on the armature have the same polarity, thus causing a repulsion torque from which the motor obtains its name.

After the motor reaches approximately 75 percent of full speed, the commutator bars of the armature winding are short-circuited by means of a centrifugal device, and the brushes are automatically moved away from the commutator. The armature then acts like a squirrel-cage rotor. The motor continues to rotate as an induction motor, just as the capacitor-start motor did (see Chapter 1).

The Centrifugal Short-circuiting Device

The centrifugal mechanism consists of several parts located in the armature. These are shown in Figure 2-5 and consist of (1) governor weights, (2) short-circuiting necklace, (3) spring barrel, (4) spring, (5) push rods, (6) brush holder and brushes, and (7) lock washers. These are assembled as shown in the cutaway view of a complete rotor in Figure 2-6.

When the armature reaches approximately 75 percent of full speed, the governor weights are thrown outward, causing the push rods to move forward. These in turn push the spring barrel forward and allow the short-circuiting necklace to contact and short the commutator bars. At the same time, the brush holder and brushes are moved away from the commutator to save the brushes and the commutator from unnecessary wear and also to eliminate objectionable brush noises.

When assembling the centrifugal device, each part must be placed in its proper position. Figure 2-6 shows the parts in the order in which they are placed in position. Note that the brush holder is part of the armature assembly.

Some manufacturers use parts that may not be identical with those shown, but they are essentially the same and have a corresponding position in the armature. When the mechanism is completely assembled, the brush holders should be spaced approximately 0.030 in. from the commutator. This distance will vary depending on the size and make of motor.

Many repulsion-start induction motors have the brush holder mounted on the end-plate assembly instead of on the armature, but the operation of this motor is similar to that of the other in all respects. Instead of the brush holder's being moved forward, only the brush springs are moved away. This has the same effect as moving the brushes away from the commutator. The centrifugal device is actuated by a governor, as before, which moves the push rods forward and causes the necklace to short-circuit the commutator.

Instead of a lock washer, a threaded shaft and nut may be used to hold the centrifugal mechanism in place. When dismantling this mechanism, it is impor-

tant to count the number of threads before taking off the nut, so that when reassembling the mechanism, the proper pressure will be placed on the governor spring. Figure 2-7 shows the order in which these parts are assembled.

Brush-riding, Repulsion-Start Induction Motor

In the brush-riding, repulsion-start induction motor, an axial commutator is used on which the brushes ride. Such a commutator is shown in Figure 2-8.

The centrifugal apparatus generally used on this motor consists of a number of copper segments held in position by an encircling garter spring, as shown in Figure 2-9. This assembly is placed in position adjacent to the commutator, so that at a preset speed, centrifugal force will cause the copper segments to short-circuit the commutator bars. The segments are returned to their original position by the garter spring when the motor stops. The motor runs as an induction motor while the commutator is short-circuited. Many types of short-circuiting mechanisms are made for this motor, but the working principle is essentially the same in all.

In the brush-riding type of repulsion-start induction motors, the brushes do not conduct any current after the motor attains speed, even though they ride on the commutator.

The number of brushes that ride on the commutator ordinarily depends on the number of poles in the motor. A four-pole motor has four brushes (Figure 2-10). Two brushes will suffice if the armature is wave wound or cross-connected, as will be explained later in the chapter (Figure 2-11). Note that in Figures 2-10 and 2-11, all the brushes are connected together or shorted. This is true of all repulsion-start induction motors, regardless of the number of poles or brushes. They are not connected to an outside line, nor are they connected to the stator winding.

Stator Windings and Connections

The stators of repulsion-start induction motors have one winding, like the running winding of the split-phase or capacitor motor. The coils of each pole are concentric and are put in the slots in exactly the same manner as in the split-phase motors. Insulation of the proper size and thickness is placed in the slots to prevent grounds.

Dual Voltage. Most repulsion-start motors are made for dual-voltage operation, regardless of the number of poles and the frequency of the current. The usual method of connecting a motor is to connect all poles in series for high-voltage operation and in two-parallel for low-voltage operation. Figure 2-12a illustrates a four-pole, dual-voltage (115–230) stator connected for 230-volt operation using the short jumper connection. Figure 2-12b shows the terminal markings used on a dual-voltage repulsion-type motor. Each wiring diagram shows four leads out of the motor which are lettered T_1, T_2, T_3, and T_4. For 230-volt operation, T_2 and T_3 are connected together and taped. The line leads are connected to T_1 and T_4. For 115-volt operation, T_1 and T_3 are connected to L_1, and T_2 and T_4 are con-

nected to L_2. Figure 2-13 shows the same motor as Figure 2-12a except that long jumper connections are used. All dual-voltage motors have four wires brought out of the motor to permit changeover from one voltage to another.

Some dual-voltage motors are connected in two parallel for high-voltage operation and in four parallel for low-voltage operation. Examples of these methods of connection are shown in Figures 2-14a and b and 2-15.

The majority of repulsion-start induction motors are wound for four-pole, 1,750-rpm operation, but some are wound for six- and eight-pole operation. Figures 2-16 and 2-17, show the stator windings of a six-pole motor, and Figures 2-18 and 2-19 show the windings of an eight-pole motor. Figure 2-18 shows long jumper connections.

Recording Data. When it is necessary to rewind the stator of a repulsion-start induction motor, care must be taken to record the proper data. Include the pitch of the individual coils, the turns, and the size of wire. Of utmost importance is recording the position of the poles in the stator. The coils of each pole must be put back into the same slots in which they were located before the windings were stripped. If the coils are put in other slots, the armature may not rotate, or if it does rotate, it may not have the desired torque.

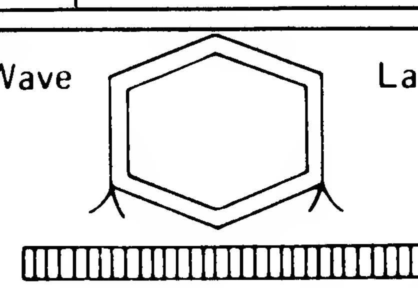
A simple method of recording the position of the original winding is to mark the center slot or slots of each pole with a center punch (see Figure 2-20). Another method is to make a drawing of the poles' position in the frame. Some motors have stator slots that are so constructed that it is impossible to make an error in winding. On these motors the section of the core at the center of each pole is wider than the other sections. This construction is shown in Figure 2-21. The method of recording the winding data is similar to that used for the other types of single-phase motors so far discussed. Figure 2-22 illustrates a typical record of the pitch data of a 24-slot, four-pole motor. Because the stator winding is similar to that of the main winding of a capacitor-start motor, it is stripped as described in Chapter 1, "Capacitor-Start Motors." A typical data sheet follows.

DATA SHEET FOR REPULSION MOTOR

Make

H.P.	R.P.M.	Volts	Amps.
Cycle	Type	Frame	Style
Temp.	Model	Serial #	Phase

Rotor	Bars	Stats	Coil Pitch	Wave Lap
Lead Pitch	Turns	Coils/Slot	Size Wire	
	Equalizer	Pitch		



Stator	Poles	Slots	Size Wire	No. of Circuits

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	1
Winding																																					

Armature Windings for Repulsion-Start Induction Motors

Armature winding is taken up in detail in Chapter 6, Direct-Current Armature Winding. However, some of the important points in the study of repulsion motors, such as cross-connections and equalizer rings, will be discussed here. This material applies not only to repulsion-start induction motors but also to repulsion and repulsion-induction motors.

Construction of the Armature. The details of the armature are shown in Figure 2-23. The core consists of laminations punched from annealed high-grade electrical sheet steel. These are tightly pressed together and then pressed onto the shaft. There is a large difference in the magnetic lines of flux between the iron teeth and the open area of the slots in both the armature and the stator. If these slots are in straight alignment, there will be an uneven torque because of this magnetic difference. This will cause a magnetic hum and can result in unwanted vibration. Skewing the laminations of either the stator or the armature prevents this problem. Figure 2-23 is an armature with skewed slots that do not align with the shaft.

Commutators of the radial type are either pressed on the shaft or screwed on, depending on the make and type of motor. Usually on small motors the commutator is pressed on, but on large motors it is screwed on the shaft. When replacing a press-on commutator, care must be taken to apply even pressure on the shaft to avoid tilting the commutator; otherwise, too much of the commutator will have to be turned down in a lathe in order to have the commutator run true. These two commutators are illustrated in Figures 2-24 and 2-25.

Some commutators can be reinsulated by taking them apart, but most commutators are constructed in such a manner that reinsulation is impossible. These commutators are assembled with a composition of Bakelite or other material that may crack when subjected to the excessive heat caused by short circuits. When a repulsion-start induction motor must be rewound because of burn-out, it is often found that the commutator must also be replaced. Radial commutators nearly always have to be replaced, but the axial type are much sturdier and can be used again.

Winding the Armature. Armature windings are either lap or wave. Figure 2-26 shows a lap winding in which the end lead of a coil is connected to a commutator bar adjacent to the starting lead of the same coil.

A wave winding is one in which the starting lead and the end lead are connected on opposite sides of the commutator for a four-pole motor (see Figure 2-27). For a six-pole motor, the starting lead and the end lead are connected approximately one-third the number of commutator bars apart; for an eight-pole motor, one-fourth the number of bars apart.

There may be the same number of coils as slots, in which case the number of commutator bars must equal the number of coils or slots. This is called a *one-*

coil-per-slot winding. Such windings are shown in Figures 2-26 and 2-27. An armature may have twice as many coils as slots. In this case, the commutator has twice as many bars as slots. This is called a *two-coil-per-slot* winding and is a very popular type of winding on small motors. It is shown in Figures 2-28 and 2-29. When each slot contains three coils, there are three times as many commutator bars as slots. This is called a *three-coil-per-slot* winding and is shown in Figures 2-30 and 2-31. Notice the pitch of the coils. In these illustrations the coil pitch is 1 and 8. All coils in an armature have the same pitch, turns, and wire size.

Winding Procedure. Assuming a two-coil-per-slot lap winding having four poles and 28 slots, the procedure for winding the armature is as follows:

1. Mark the core on each side of one coil with a file and trace the leads of this coil to the commutator bars to which it connects. These bars are also file marked. Determine by measurement the number of bars to the left or right of the slot to which the leads of this coil connect. This is done by stretching a string from the center of the slot to the commutator to see which commutator bar lines up with the slot. The number of bars to the left or right is recorded as shown in Figure 2-32.

Strip the armature and record all necessary data such as coil pitch, number of turns, type of winding (lap or wave), coils per slot (one, two, or three), pitch of leads, size of wire, and so on. Stripping an armature is explained in Chapter 5, page 175.

After the armature is stripped and the data taken, test the communicator for faults.

If the commutator is not badly worn or otherwise damaged, the following procedure may be used to prepare it for rewinding: When stripping the armature, cut the leads at least an inch from the commutator and straighten them. Chuck the armature in the lathe, and with an acetylene torch, heat the commutator while the lathe spins it. Wear a protective face shield during this procedure. When the solder softens, stop the lathe and pick out the wires with a pair of needlenose pliers. Do not overheat the commutator, but apply only enough heat to soften the solder. It may be necessary to reheat the commutator several times before all the wires are removed.

After the commutator cools, clean the mica between the bars with a commutator file or a hacksaw blade. Next use a test light to test for shorts between each bar and between each bar and the shaft. If there are no shorts or grounds, the commutator does not need to be replaced.

If it is of the radial type and replacement is necessary, the portion of the commutator into which the short-circuiting mechanism fits will have to be bored out and enlarged to accommodate the necklace. This is done on the lathe with a boring tool either before or after winding. Extreme care must be exercised, as some commutators may be easily broken if not handled properly.

Before new insulation is placed in the slots, remove all the old insulation. Appropriate insulation about 0.007 to 0.015 in. thick is usually sufficient for motors of less than three horsepower. The insulation, preferably cuffed, must extend on either side of the core about 1/4 in. and cut a trifle below the top of the slot. To insulate a stator, the procedure is, generally, to replace the insulation with the same quality and thickness of insulation as the motor originally contained.

2. Set up the armature on horses in the position shown in Figure 2-33a or in an armature holder shown in Figure 2-33b, and start winding with two wires of the same size in hand. To identify the wires, it may be necessary to test each wire end when it is placed into the commutator bar. This can be avoided by using sleevings of different colors for lead identification or by cutting the end leads of different lengths. Sometimes wires of different colors are used.

Place the beginning leads of the two wires in the notches of the correct two commutator bars according to the data taken. These wires are usually tapped lightly with a drift punch to secure them in the notches. Make sure that all insulation on each wire is removed before putting it into the notch. Wind the proper number of turns and cut the wires at the slot nearest you, allowing sufficient length of leads for connection to the bars. Bend the wires back on the core.

3. Start the next two coils in the next open slot and put the beginning leads in the next two bars, as shown in Figure 2-34. Wind the proper number of turns; then cut the wires and bend them back on the core, as was done with the previous coils. This procedure is continued until the entire armature is wound.

4. When all the coils are wound, the end leads of each coil should be resting on the core ready to be connected to the commutator bars. Place each end lead in the notch of the commutator bar adjacent to the beginning lead of that coil, as illustrated in Figure 2-35. Thus, each notch holds two leads—a beginning lead on the bottom and an end lead on top. Wedges are fitted into each slot on top of the wires in order to prevent the wires from being thrown outward by centrifugal force when the armature rotates.

If the armature is coil wound, that is, if the coils are made up on a form and then put into the armature, the method of placing the coils in the slots is slightly different. When the armature is coil wound, only the bottom side of each coil for the first one-fourth of the total number of slots is placed therein. The entire coil is then put into the slots. In other words, the top side of the coil is not placed in a slot until the bottom half of the slot has a coil unit.

Make sure that the top leads are connected in the right order to avoid having reversed coils. After all the leads are connected, complete the winding by soldering all leads, testing, varnishing, and turning down the commutator.

Equalizer or Cross-Connections. Cross-connections are lengths of insulated wire that connect commutator bars of the same potential. For a four-pole motor these commutator bars will be 180 mechanical degrees apart; for a six-pole motor, bars 120 degrees apart are connected. These connections are generally

placed behind the commutator bars and should be made with the same size of wire as the armature winding. New commutators are often supplied with the cross-connections already in place.

Nearly all lap-wound armatures used on repulsion motors are cross-connected. Circulating currents due to unequal air gaps between the armature and the stator are thus minimized. Such currents occur when a worn bearing causes the bottom side of the armature to be closer to the stator than the top side. In addition, the use of two brushes instead of four on a four-pole motor is permitted. On some armatures, the cross-connections close the circuit through the armature.

To determine the bars in which cross connections are placed, it is necessary to know the number of bars, the number of poles, and whether the commutator is completely cross-connected or half cross-connected. A completely cross-connected commutator is one in which all commutator bars contain equalizer wires.

To determine the number of bars spanned by each cross-connection, use the formula

$$\text{Span} = \frac{\text{no. of bars}}{\text{no. of pairs of poles}}$$

For example, if a commutator has 50 bars and if the motor has four poles, the span will be

$$\text{Span} = \frac{50}{2} = 25 \text{ bars}$$

Therefore, to span 25 bars, the first cross-connection will be between bars 1 and 26; the next connection is between 2 and 27; and so on. If a six-pole motor has 81 commutator bars, the equalizer span will be 81/3 = 27 bars, and cross-connections are made between bars 1 and 28, 2 and 29, 3 and 30, and so on. Figures 2-36, 2-37, and 2-38 illustrate a 36-bar commutator cross-connected for four, six, and eight poles.

On lap windings that have no cross-connections, it is necessary to have as many brushes as poles. On cross-connected commutators, only two brushes are necessary, although more may be used.

If cross-connected armatures are tested for shorts on the growler, a hacksaw blade will vibrate completely around the armature, ordinarily indicating a short circuit. However, if this is not the case, and to determine whether or not the armature is shorted, it is necessary to use a meter for testing. Another method of testing for a shorted armature is described on page 86.

Rewinding a Wave-wound Armature. The method of winding a wave-wound armature is similar to that for a lap-wound armature, except for the position of the leads in the commutator. Figure 2-39 shows a commutator for a 23-slot,

four-pole armature having 45 bars. It has two coils per slot and is to be connected as a retrogressive wave winding. The procedure for winding this motor is as follows:

1. Record all necessary data, being careful to note the commutator pitch. The formula for determining the commutator pitch of a retrogressive winding is

$$\text{Commutator pitch} = \frac{\text{no. of bars} - 1}{\text{no. of pairs of poles}} = \frac{45 - 1}{2}$$
$$= 22, \text{ or } 1 \text{ and } 23$$

Any four-pole, wave-wound armature must have an odd number of commutator bars. If the commutator has an even number of bars, two of them must be shorted.

Because the armature has two coils per slot, there are 2 × 23, or 46, coils called for in the armature. However, only 45 coils can be connected to the 45-bar commutator. Therefore, one coil is not connected in the armature circuit. Nevertheless, the dead coil must remain in the armature for mechanical balancing (see Figure 2-40).

In all two-coil-per-slot, four-pole, wave-wound armatures, it is necessary to add a coil in the form of a jumper lead when the number of bars is one more than the number of coils. For instance, if the armature had 22 slots instead of 23, only 44 coils could be wound on the armature; but because 45 are necessary, an extra coil is put on the armature by connecting a jumper between the commutator bars that would ordinarily have been used for the forty-fifth coil. Figure 2-41 shows the connection of such a jumper lead.

2. Start winding the armature by hand with two wires, and place the bottom leads in the proper bars according to the data. The leads are placed away from the center of the coil, as shown in Figure 2-42. This is nearly always the case in wave-wound armatures.

Wind the proper number of turns for each coil; then cut the wires, one long and one short for identification, and bend them back on the core. If the armature is coil wound, apply colored sleeving on each lead before it is placed in the armature slots.

3. Connect beginning leads into the commutator bars and wind the next two coils, as shown in Figure 2-43. If the armature is coil wound, the coil is placed in the slots *before* the beginning leads are connected to the commutator bar.

4. After the coils are wound, the end leads are put in the commutator bars on top of the beginning leads, as shown in Figure 2-44. The first top lead is usually tested to make sure it is placed in the right commutator bar. All the others are put down in sequence, as each one is identified either by its length or by its color. It is essential that the proper commutator pitch be used, otherwise the armature may not operate. In this wave winding, the top and bottom leads go away from each other. In a lap winding, the leads go toward each other.

5. The procedure from here on is the same as that given for dc armatures in Chapter 5. The armature can be tested for shorts on the growler as described on page 181.

Reversing the Repulsion-Start Induction Motor

If a closed coil of wire is placed alongside and in the same plane as a field pole supplied with alternating current, the coil will turn until it is at right angles to the field pole, as illustrated in Figure 2-45. For this to take place, the coil must be slightly tilted; otherwise a torque will be produced in both a clockwise and a counterclockwise direction, with the result that the coil will not turn at all. The current induced in the coil of wire causes a pole to be formed similar in polarity to that of the field pole. Consequently, the two poles are repelled from each other, until the movable one rotates to the horizontal position.

Figure 2-46 shows the armature of a repulsion motor substituted for the coil. If the two brushes of a two-pole motor are shorted, as shown by the heavy line in Figure 2-46, the current induced by the stator winding into the armature winding by the transformer action will cause poles to be formed on the armature core, identical with those on the stator core. No motion takes place because the repelling forces on both sides of the rotor are in a horizontal direction. The stator winding is usually known as the *inducing winding*.

If the brushes are shifted either to the right or to the left (shown in dashed lines in Figure 2-46), the armature will rotate just as it did in the case of the closed coil. If the brushes are shifted clockwise, the armature will rotate in that direction. And if the brushes are shifted counterclockwise, the armature will rotate in that direction. Thus, a repulsion motor is reversed by shifting the brushes 15°. Actually, to shift the brushes, the entire brush-holder assembly or rocker arm must be moved. Usually there are markings on the end bracket, like those shown in Figure 2-47, that correspond to the direction of rotation. To reverse a motor, a small screw on the brush holder bracket is loosened, and the brush holder is shifted to either of the two marks. The screw is then tightened before the motor is started. This method of reversing applies to both brush-riding and brush-lifting types of motors.

Stationary Brush Holders. Many motors, especially the brush-riding type, do not have movable brushes. The brush holders may be cast as part of the end bracket and therefore cannot be moved. Some of these motors are constructed so that the field poles are off center. If the entire pole frame is reversed, the effect will be the same as if the brushes were shifted. On some motors, additional stud holes in the stator are provided to permit the stator to be moved. To reverse such a motor, the end brackets are removed, the frame reversed end to end, and the motor reassembled. The two positions are shown in Figures 2-48 and 2-49.

Cartridge Brush Holders. Another type of motor has two off-center brush holders, which are individually moved. To reverse such a motor, each brush

holder is moved 180 mechanical degrees. On some motors, the entire brush holder is removed and then set back in place after it is turned through 180 degrees. On other motors, a small setscrew is loosened, and the brush holder is turned by means of a screwdriver. These brush holders are illustrated in Figures 2-50 and 2-51. They usually have an arrow on the cap indicating the direction of rotation. Turning the off-center brush holders shifts the brushes to a new position on the commutator and produces reversed rotation.

Some motors are constructed for only one direction of rotation. On motors of this kind the brush holders cannot be shifted, nor can the frame be moved. One good way to reverse such a motor is to unsolder the commutator leads and move them over several bars, but this cannot always be done. Another method is to rewind the stator so that the center of each pole is moved at least one slot away from its original position.

Making a retrogressive winding from a progressive one will not usually reverse the motor, as it does in a dc armature. However, on some motors reversal of rotation may result.

Brushes. Motor brushes are made in different sizes, shapes, and grades, depending on the individual machine. Because they carry current and ride on the commutator, they will wear and consequently must be replaced. A good rule to follow is to replace with a brush identical with that in the motor. Replacements can easily be obtained by ordering from supply houses, using the nameplate data as information.

Most brushes are made from some form of carbon or graphite. Ordinarily these materials are processed so that they will be suitable for operation in the motor for which they are intended. The treatment consists of subjecting the carbons to high temperatures and pressures, resulting in brushes with different characteristics such as hardness, electrical and thermal conductivity, and toughness. Some brushes are made from a mixture of powdered metal with graphite to carry larger current than can be obtained from graphite alone.

Brushes are made in various shapes and usually equipped with a short length of stranded copper wire called a *pigtail*. The purpose of the pigtail is to conduct current from or to the brush proper and may or may not be connected to the brush holder, depending on the type of motor. On repulsion-start motors having radial commutators, the brush is wedge shaped so that it will resemble the shape of the commutator bar, wide on top and narrower on the bottom. These brushes usually come in pairs with a pigtail between them, as shown in Figure 2-52, and do not connect to the brush holder.

Locating the Neutral Point. If new marks are to be made in the end bracket for clockwise and counterclockwise rotation, it is first necessary to locate the neutral point or setting of the brushes. At this setting, the motor will not run in either direction. Two such points will be found in the ordinary repulsion-start induction motor, one of which is the correct setting (hard neutral) and the other the incor-

rect one (soft neutral). To determine which is correct, move the brushes to a point that the motor does not run in either direction and then shift the brush holder slightly to the right of this point. The motor should then run in a clockwise direction. Next shift the brush holder to the left of the neutral point. The motor should then run counterclockwise. If the motor runs in the direction in which the brushes have been shifted, the correct neutral (hard neutral) point has been used. If the wrong neutral point has been used, shifting the brush holder to the right will produce counterclockwise rotation.

THE REPULSION MOTOR

The repulsion motor is distinguished from the repulsion-start induction motor by the fact that it is made exclusively as a brush-riding type and does not have any centrifugal mechanism. This motor both starts and runs on the repulsion principle. In common with a dc series motor, it has a high starting torque and a variable-speed characteristic. It is reversed by shifting the brush holder to either side of the neutral position. Its speed can be decreased by moving the brush holder farther away from the neutral position. This motor is sometimes called an *inductive-series motor.*

The stator of the repulsion motor is like that of the repulsion-start induction motor, and the stator poles are connected in the same manner. The stator is generally wound for four, six, or eight poles. Usually four leads are brought out for dual-voltage operation.

The rotor consists of an armature constructed in the same manner as the dc type. It is laminated and generally skewed. The winding may be either hand or coil wound and is connected by either lap or wave. The commutator is the axial type, and the brushes always ride on the commutator. The brushes all are connected together, as in the repulsion-start motor. Figure 2-53 illustrates a four-pole repulsion motor.

Compensating Winding

Some repulsion motors use an additional winding called a *compensating winding,* whose purpose is to raise the power factor and provide better speed regulation. The compensating winding is much smaller than the main winding and is usually wound in the inner slots of each main pole and connected in series with the armature. Figure 2-54 shows the compensating winding and its connections to the brushes. Four brushes are necessary. Two of these are connected together, and the other two are connected in series with the compensating winding. The motor illustrated may be connected for dual-voltage operation. To reverse this motor, it is necessary to reverse the compensating leads as well as to shift the brush holder. A typical data layout diagram for a 36-slot, six-pole motor of this type is shown in Figure 2-55.

THE REPULSION-INDUCTION MOTOR

It is sometimes impossible to tell the difference between the repulsion-induction motor and the repulsion motor by external appearance. However, the repulsion-induction motor has a squirrel-cage winding on the armature in addition to the regular winding. The squirrel-cage winding is located underneath the slots of the armature, as shown in Figure 2-56. The armature is usually lap wound and cross-connected.

To tell the difference between a repulsion and repulsion-induction motor, connect the motor to the line and permit it to reach full speed. Then raise all brushes so that they no longer contact the commutator. If the motor continues to operate at full speed, it is a repulsion-induction motor.

Repulsion-induction motors are made in sizes up to about ten horsepower. They are dual-voltage types and can be used for general-purpose duty. Figure 2-57 illustrates the connections of this motor for a 230-volt operation. In the field of repulsion motors, this type is becoming very popular, because of its good all-round characteristics, which are comparable to those of the dc compound motor.

The advantage of this motor is that no centrifugal short-circuiting mechanism is used. It has a high starting torque and, owing to the squirrel-cage winding, a fairly constant speed regulation. These motors are also made with compensating coils to increase the power factor of the motor circuit. An illustration of a compensated repulsion-induction motor connected for a 115-volt operation is shown in Figure 2-58.

ELECTRICALLY REVERSIBLE REPULSION MOTORS

Repulsion motors are reversed usually by shifting the brush rigging approximately 15° either side of neutral. Actually, the direction of rotation depends on moving the brushes mechanically from one side of hard neutral to the other. The rotation can be reversed by moving the magnetic field instead of the brushes. The brushes remain in a fixed position at all times. This is done by using two sets of windings on the stator instead of one. These are wound 90 electrical degrees apart, just like the windings on a split-phase motor.

There are several ways of arranging the windings for the electrically reversed repulsion motor. The main or inducing winding is wound on the stator as heretofore described, and the reversing winding is wound 90 electrical degrees from the main winding. Both windings are connected in series. To reverse the motor it is necessary only to reverse the leads of either winding.

Another method of winding is to wind the reversing winding in two sections. In operation, the main and one section are connected in series for clockwise rotation. For counterclockwise rotation, the main winding is connected in series

with the other section. The two sections are so connected as to give opposite polarities for the same pole. This procedure shifts the magnetic axis either to the left or right, producing the required rotation. Schematic diagrams of these and other repulsion-type motor connections are shown in Figure 2-59, reproduced through the courtesy of NEMA.

REWINDING AND RECONNECTING REPULSION MOTORS

Rewinding for a Change in Voltage

Rewinding for a change in voltage is the only change that does not cost too much. Only the stator winding must be changed. The rules in this change are similar to those in the split-phase or capacitor main winding.

RULE 1.

$$\text{New turns} = \frac{\text{new voltage}}{\text{orig. voltage}} \times \text{orig. turns/coil}$$

RULE 2.

$$\text{New c.m. area} = \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}$$

EXAMPLE:

A 115/230-volt repulsion-start induction motor is to be changed to a 230/460-volt motor.

Solution:

$$\text{New turns} = \frac{230}{115} \times \text{orig. turns}$$
$$= 2 \times \text{orig. turns}$$

Therefore, twice as many turns per coil are used.

$$\text{New c.m. area} = \frac{115}{230}\ \text{orig. c.m. area}$$
$$= \frac{1}{2}\ \text{orig. c.m. area}$$

Therefore, wire one-half of the original gauge is used. For example, if the original wire size was No. 16, use a No. 19 instead.

In a voltage change, the armature need not be disturbed in any way.

TROUBLESHOOTING AND REPAIR

Testing

As in the case of other motors, repulsion motors are tested for grounds, shorts, opens, and reverses. Both the armature and stator must be given these tests.

Test for Grounds. The usual method of testing the stator for grounds is to use the test lamp. Connect one test wire to the frame and the other test wire to a stator lead. If the lamp lights, a ground is indicated. The method of location and repair of the ground is the same as that described for the split-phase and capacitor motors.

The armature windings and the commutator are tested for grounds in exactly the same way. On some motors, the brush holders are grounded to the end plate. Consequently, before the armature is tested for grounds, the brushes must be lifted away from the commutator. If a ground is indicated in the armature, test for location by the meter method as described in Chapter 5. A voltage of approximately 1,000 volts, applied between winding and ground, may flash at the point of ground and show its location.

Test for Shorts. The stator is tested for shorts by using the internal growler, by measuring the drop in voltage across each pole, by a resistance measurement of each pole, or by feeling for the hottest coil after the motor runs for a short time. A shorted coil can also be detected by applying direct current to the winding and determining the strength of each field with a piece of iron. The pole having the least attraction or pull is the shorted one. If a coil is burned or charred, visual inspection alone will reveal the defective coil.

The armature is tested for shorts with the millivoltmeter, or it may be tested on the growler if the armature is wave wound. It must be emphasized that lap-wound armatures with cross-connections cannot be tested on the growler. Shorted coils produce a low reading on the millivoltmeter and, if tested on the growler, cause a hacksaw blade to vibrate. This is explained in Chapter 5.

A highly satisfactory method of testing for a short circuit in the armature of a repulsion motor is illustrated in Figure 2-60. Remove the brushes or prevent them from contacting the commutator. Connect the power line to the motor. With the brushes removed, the motor will not rotate. Turn the armature by hand, and if there is a shorted coil in the armature, it will tend to stick at certain points. Otherwise the armature will turn freely. This test should be made only if the bearings are in good condition.

Test for Opens and Reverses. The stator winding of the repulsion motor is tested for opens and reverses as described in the previous chapters. The armature is tested for such trouble in the manner described in Chapter 5.

Repairs

This section applies to all three types of repulsion motors. The symptoms that are encountered in practice are given below. Under each are listed the possible troubles. The numbers in parentheses after each trouble indicate the correspondingly numbered remedies to be found in the following pages.

Because only the repulsion-start induction motor has a centrifugal short-circuiting mechanism, it is only this type that is referred to when the centrifugal switch is mentioned.

1. If the motor fails to start when the switch is closed, the trouble may be
   a. Burned-out fuse.
   b. Worn bearings (1).
   c. Brushes stuck in holder (9).
   d. Worn brushes (9).
   e. Open circuit in stator or armature (2).
   f. Wrong brush-holder position (5).
   g. Shorted armature (3).
   h. Dirty commutator (9), (12), (17).
   i. Wrong lead connections (6).
   j. Necklace shorting the armature (11).
2. If the motor does not start properly, the trouble may be
   a. Worn bearings (1).
   b. Dirty necklace or commutator (9), (12).
   c. Brushes moving from commutator too soon (10).
   d. Centrifugal mechanism not assembled properly (14).
   e. Brush holder set in wrong position (5).
   f. Short-circuited mechanism worn, broken, or improperly assembled (14).
   g. Governor weights jammed (15).
   h. Improper tension in the spring (16).
   i. Shorted armature (3).
   j. Excessive end play (8).
   k. Overload (7).
   l. Shorted stator (4).
   m. Worn lip on brush holder (18).
3. If the motor becomes excessively hot, the trouble may be
   a. Motor connected for 115-volt operation but being run on 230 volts.
   b. Shorted armature or stator (3), (4).
   c. Overload (7).
   d. Worn bearings (1).
   e. Broken or burnt necklace (12), (13).
   f. Brush holder out of position (5).

4. If motor is noisy in operation, it may be caused by
   a. Worn bearings or shaft (1).
   b. Loose centrifugal device (14).
   c. Shorted stator coil (4).
   d. Excessive end play (8).
   e. Dirty short-circuiting device (12).
5. If the motor burns out a fuse, the trouble may be
   a. Grounded field (19).
   b. Incorrect connections (6).
   c. Brushes not contacting commutator (9).
   d. Shorted armature (3).
   e. Incorrect setting of brushes (5).
   f. Frozen bearings.
6. If the motor hums but does not run, the trouble may be
   a. Wrong lead connections (6).
   b. Worn bearings (1).
   c. Incorrect brush setting (5).
   d. Shorted armature (3).
   e. Shorted stator (4).
   f. Grounded stator (19).
   g. Brushes sticking or not making contact (9).
   h. Dirty commutator (9), (12).
7. If the motor does not come up to speed, the trouble may be
   a. Wrong spring tension on brushes (10), (16).
   b. Dirty or burned necklace (12).
   c. Dirty commutator (9).
   d. Shorted armature (3).
   e. Shorted stator coil (4).
   f. Worn bearings (1).
   g. Push rods too long (10).
8. If the motor sparks internally, the trouble may be
   a. Open armature coils (2).
   b. Dirty commutator (9).
   c. High mica (20).
   d. Short or sticking brushes (9).

1. Worn Bearings. If the bearings are so worn that the rotor touches the stator, the motor will hum when the switch is closed, and the armature will have only a slight tendency to rotate. With no voltage applied to the motor, test the bearings by trying to move the shaft vertically. Movement indicates worn bearings, and the remedy is replacement with new bearings. When the bearings are in such a condition, the armature has smooth worn sections on the core, indicating that it has been rubbing against the stator. If the bearings are slightly worn, the motor will be noisy and run hot, and in some instances it will run at a slower-than-normal speed.

2. *Open Circuit in Stator or Armature.* To locate the position of the open, use the test lamp and proceed as described in Chapter 1. After the open is located, repair or rewind as the case demands.

In testing the stator for opens in a repulsion motor, make certain to test two circuits. Because nearly all repulsion motors are dual-voltage motors, four leads are brought out, two for each set of poles.

Opens in the armature are tested and located with a meter, as in the case of dc motors. A burned spot on the commutator will indicate the position of the open coil. The remedy is to repair the open by reconnecting the broken wire or, if the break is not readily accessible, by rewinding the entire coil or armature.

3. *Shorted Armature.* If most of the coils of an armature are shorted, the motor will make a feeble attempt to start, then hum, and remain inoperative. If only one or two coils are shorted, the motor will run but will have a poor starting torque. The shorted coil will become hot at start and may smoke if the starting is prolonged.

When a shorted coil is placed in a changing magnetic field, it will have a voltage induced into it. The short provides a completed circuit, and so current will flow within the shorted turns. Not only does the current flow create heat in the coil; the coil also will set up a magnetic pole that will conflict with the motor's normal poles. This will weaken the torque, and a normal load will be too much for the motor to pull.

A good method of testing an armature for shorted coils is to remove the brushes and then turn the armature while current is flowing through the stator. If the armature turns freely without sticking, it is in good condition. Usually a visual inspection of the armature winding of a repulsion motor will reveal shorted coils. The armature is generally completely burned and charred so that the odor of burnt insulation is evident.

It is not a good policy to cut out coils on repulsion motors. If one or more coils are shorted, the entire armature should be rewound. Be sure the commutator is perfect before the armature is rewound.

4. *Shorted Stator.* A shorted stator will cause the motor to run at a slower-than-normal speed and produce a growling noise. In addition, the shorted coils will become hot and smoke. Sometimes the motor will not reach the speed required for the centrifugal mechanism to operate, and consequently, it will draw an excessive current and burn out a fuse. Test for this condition with an internal growler.

5. *Wrong Brush-Holder Position.* On repulsion motors, the brush holder must be set in a definite position for rotation. If the holder moves from this position, either the motor will have poor starting torque or it may not run at all, and a fuse will burn out. This condition will occur when the setscrew holding the brush

rigging in place becomes loose and permits the holder to shift. A similar condition arises when the armature is rewound and the leads are not put in the proper commutator bars. If the leads are placed one or two bars away from the proper position, a new neutral point must be located.

This will also occur if the stator has been rewound and the coils placed one slot away from the original position. In either case, a new neutral position must be located, and from this, the new position for clockwise and counterclockwise direction is located. This can be found by shifting the brush holder back and forth until the motor has the required torque.

6. Wrong Lead Connections. Figures 2-61 and 2-62 show the errors that are sometimes made by beginners when connecting the four external leads of a repulsion motor. In both cases, the motor will hum when power is applied. To remedy this, reverse one set of motor leads.

Another error made in the lead connections is joining terminals T_1 and T_2 together and to line L_1, and terminals T_3 and T_4 together and to line L_2. Study of the diagram of Figure 2-63 shows that such a connection is equivalent to having an open circuit. With this connection, the motor will not even hum when connected to the line.

7. Excessive Load. Overloading a motor prevents it from operating at the required speed and causes an excessive flow of current. In repulsion-start induction motors, the centrifugal mechanism will not operate because the speed will be insufficient. Instead, they will attempt to operate as repulsion motors and will be noisy and very hot.

8. Excessive End Play. On some repulsion-start induction motors having radial commutators, excessive end play will cause the brush holder to be too great a distance from the commutator, resulting in poor brush pressure which will produce sparking and may prevent the motor from coming up to speed. Allow at the maximum 1/64-in. end play by placing washers on the shaft of the armature. Make sure, however, that the washers are so placed that the core of the armature lines up with that of the stator. Quite often, excessive end play will cause noisy operation.

9. Brushes Not Contacting Commutator. If the brushes are stuck or worn, they may not touch the commutator, and the motor will not start. A dirty commutator or poor spring tension will have the same result. If the motor does start, considerable sparking will occur. These defects are easily detected by inspection and are remedied by cleaning the commutator, renewing the brushes or springs, or renewing both.

10. Brushes Lifting from Commutator Too Quickly. A repulsion-start induction motor operates as a repulsion motor until it reaches approximately 75 percent of full speed and then comes up to speed as an induction motor. It is obvious

that if the brushes are moved away from the commutator before this speed is reached, the motor will not attain full speed. Instead, it will slow down, causing the brushes to ride on the commutator again. This cycle of operations may continue indefinitely.

Premature movement of the brushes from the commutator may be due to poor spring tension. On the type of motor that has the brush-holder assembly on the armature, it may be necessary to replace the spring. On the other type, the tension on the spring may be increased by tightening the nut.

If the push rods are too long, the brush holder is held too far away from the commutator. At start, the brush holder should be approximately 1/32 in. from the commutator. The push rods should be shortened when the commutator is turned down on the lathe. Incorrect assembly of the centrifugal mechanism will also cause premature movement of the brush holder.

11. Necklace Shorting the Armature. It is usually the fault of the assembly when the necklace shorts the armature. This can easily be rectified by referring to Figure 2-6 and reassembling the parts in the proper order, as shown there.

On the brush-riding, repulsion-start motor, the short-circuiting segments may become welded to the commutator bars, or the commutator bars may become grounded.

12. Dirty Centrifugal Necklace or Commutator. If the necklace is dirty or broken or if the part of the commutator that is shorted by the necklace is dirty, then the commutator will not become entirely shorted at the right time. Consequently the motor will run in a manner similar to that of a squirrel-cage rotor with open-circuited bars. Such a motor will not pull a load and will slow down and overheat. The motor will also be noisy. The brush-lifting type will slow down sufficiently so that the brushes will again ride on the commutator, and this in turn will make the motor speed up. But as soon as a load is placed on it, it will slow down again. This operation will repeat itself until a fuse blows.

The remedy is to remove all the mechanism and clean the necklace, replacing parts if necessary. The commutator must also be cleaned thoroughly.

13. Short-circuiting Necklace Broken or Not Operating Properly. If the necklace is of the type consisting of many individual pieces of copper segments held together with a length of wire through holes in each piece, make sure that it is placed on its holder so that the holes are toward the rear of the commutator. Each segment also has a shoulder that must be in a position to contact the commutator.

If the necklace is the one-piece type, it is so constructed that it curves. It is important that it be assembled on the necklace spool to fit the curvature of the spool.

If the necklace is broken, burned, or assembled improperly, the armature may not be completely shorted after it reaches speed. The motor then operates at all times as a repulsion motor. The remedy is a new necklace or proper assembly.

14. Centrifugal Mechanism Not Assembled Properly. If the necklace is assembled in such a position that it always short-circuits the commutator, the motor will not start. If the spring barrel is assembled improperly, the mechanism will jam. Incorrect tension on the spring will cause the brushes to lift from the commutator too quickly or too slowly. An improperly assembled mechanism may also be loose and cause this condition during operation.

If the centrifugal device is suspected, dismantle it entirely, clean all parts, make sure that each part is in perfect condition, and then reassemble correctly. Use Figure 2-6 as a guide.

15. Centrifugal Weights Jammed. When the centrifugal weights are jammed, the motor operates as a repulsion motor at all times; it will be noisy and have poor torque. If the weights are jammed, the push rods will not operate, and consequently the short-circuiting apparatus will be inoperable. Further, the brushes will ride on the commutator at all times. This will also cause severe overspeeding with most types of loads. The armature and brushes are not designed to work as a repulsion-type motor, and so if they are allowed to run this way very long, they will overheat and burn out.

16. Incorrect Tension of the Spring. If the spring tension is insufficient, the commutator will become shorted at a very low speed, and the brushes will be lifted from the commutator too quickly. This will have the effect of producing a low starting torque, and the motor will be unable to achieve the speed necessary to change over from the repulsion-start to the induction-run condition. The spring may have to be replaced or adjusted for the proper tension.

If there is too much tension, the brushes will not release, nor will the armature become shorted. This will cause the motor to run as a repulsion motor at all times, with resultant noisy operation and sparking. Remedy this fault by adjusting the nut for the proper tension.

17. Dirty Commutator. This condition is similar to that of sticking brushes, as no current will flow through the armature if dirt on the commutator prevents the brushes from making contact on the commutator. If such a condition exists, the motor will hum, and there may be sparking between the commutator and the brushes. The remedy is to clean the commutator with a clean cloth and sandpaper.

18. Worn Lip on Brush Holder. A worn lip on a brush holder is a common cause of failure, particularly when the holder is of white metal. The worn lip causes the holder to wobble and give poor brush contact. To remedy, replace the brush holder.

19. Grounded Field. If the field is grounded in one place, the operator may get a shock if the motor is touched. If the frame of the motor is grounded according

to code regulations, a fuse will blow. Two or more grounds on the field winding are equivalent to a short and in nearly all cases will cause a fuse to blow. The motor may hum for a while before the fuse blows.

20. High Mica. When the copper bars of a commutator wear more than the mica strips between the bars, the condition known as *high mica* develops. The high mica does not allow the brushes to make good contact with the commutator, and sparking is caused. The remedy is to turn down the armature in a lathe and then undercut the mica.

Chapter 3

THREE-PHASE MOTORS

VARIETIES OF THREE-PHASE MOTORS

Three-phase motors vary from fractional-horsepower size to thousands of horsepower. These motors have a fairly constant speed characteristic and are made in designs giving a variety of torque characteristics. Some three-phase motors have a high starting torque; others, a low starting torque. Some are designed to draw a normal starting current; others, a high starting current. They are made for practically every standard voltage and frequency and are very often dual-voltage motors. Three-phase motors are used to drive machine tools, pumps, elevators, fans, cranes, hoists, blowers, and many other machines.

Construction of Three-Phase Motors

A three-phase motor is shown in Figure 3-1. It has three main parts: stator, rotor, and end plates. Its construction is similar to that of the split-phase motor, but it has no centrifugal switch.

The stator is shown in Figure 3-2 and consists of a frame and a laminated steel core like that used in single-phase motors and a winding formed of individual coils placed in slots. The rotor may be a die-cast aluminum squirrel-cage type or a wound rotor. Both types contain a laminated core pressed onto a shaft. The squirrel-cage rotor is shown in Figure 3-3 and is like that of a capacitor-start motor. The wound rotor is shown in Figure 3-4. It has a winding on the core that is connected to three slip rings mounted on the shaft.

The end plates or brackets are bolted to each side of the stator frame and contain the bearings in which the shaft revolves. Either ball bearings or sleeve bearings are used.

Operation of Three-Phase Motors

The coils in the stator's slots are connected to form three separate windings called *phases*. These are shown in Figure 3-5. Each winding or phase is connected in the same way as is a single-phase run winding. The same connection rules apply to these phases that apply to a single-phase run winding. Adjacent

poles must be connected to have opposite polarity, and they may be connected long or short jumper. The number of circuits per phase will be any number that will divide evenly into the number of pole groups. For example, a phase with four pole groups can have one, two, or four circuits.

The following explanation pertains to a four-pole, 36-slot motor. (''Chord Factor'' in Chapter 1 explains degrees per tooth.) Each pole group is placed in the stator slots and connected so that they will be 120 electrical degrees from the other. Figure 3-6a shows the 120° slot in a concentric-wound coil group, and Figure 3-6b shows the 120° slot in a lap-wound coil group. The coil in the 120° slot is the start of the group of the next phase. Figure 3-7 shows three coil groups that are spaced 120° from one another. The illustration shows only the coils of each phase that are of the same polarity. The rest of the coils that are wound with them have been left out for clarity.

The rotation in a three-phase motor is accomplished by a rotating magnetic field in the stator reacting to the squirrel-cage winding of the rotor. The rotating magnetic field is created by three separate voltages energizing the three-phase windings explained above. Each voltage reaches its peak value 120 electrical degrees in time after the other (1/180th of a second).

Each winding is spaced 120 electrical degrees from the other, as shown in Figure 3-7. Electrical degrees are used in a stator to measure where to place the poles: 360 electrical degrees equal two poles, one north and one south pole, and one cycle of ac electricity equals 360 electrical degrees. The degrees of a cycle measure the time it takes to generate that cycle. On 60-cycle-per-second (Hz) power, one cycle takes 1/60 of a second. Figure 3-8 shows how one cycle of a single phase looks in the form of a sine wave. Figure 3-9 depicts a three-phase sine wave. The three-phase sine wave is actually three single-phase sine waves spaced 120 electrical degrees in time from one another. The voltage of each sine wave peaks in value or reaches full voltage 120° or 1/180 of a second apart. When each of these voltages are fastened to a phase winding, the windings each reach their full magnetic power 120° or 1/180 of a second after the other. This 120° magnetic timing and the 120° spacing of the windings in the stator create a rotating magnetic field. Figure 3-10 illustrates the poles and the way they fit the sine wave. Figure 3-11a shows a two-pole stator with direct current applied to phase *A*. This represents the 90° spot on phase *A* of the sine wave and the peak magnetic power of phase *A*'s winding. The bar magnet representing the rotor aligns itself as shown. In Figure 3-11b, phase *B* is energized. This happens 1/180 of a second, or 120°, later on 60 Hz, as shown on the sine wave. The bar magnet aligns itself with the center of phase *B*'s winding. In Figure 3-11c, phase *C* is energized. This happens 120°, or 1/180 of a second, after phase *B* has reached its peak power and aligns with the bar magnet as shown. Phase *A* is again energized, as shown in Figure 3-11d, and completes the revolution.

This is a simplified explanation of the way a three-phase motor works. But with three-phase power and a squirrel-cage induction, three-phase motor, the explanation becomes much more complicated.

The Squirrel-Cage Rotor

Poles form in a stator around a spot where the current flows in opposite directions in the slots on either side. Figure 3-12 illustrates how this happens in a stator. Poles are formed in the rotor in much the same way. The lines of force from the rotating magnetic field cut the rotor bars, inducing a low voltage into them. The end rings short out the rotor bars, providing a circuit in which the current can flow. Figure 3-13 shows how the poles form. The lines of force from pole 1 cut the bars of the rotor, creating a current flow as shown; pole 2 creates the current flow in the opposite direction. The end rings carry the current from bar to bar. The bars between the poles are not cut by the lines of force, and so they produce no voltage. The current in the bars above and below the bars with no voltage is flowing in opposite directions, and a pole is formed at this spot. This spot is at a 90° angle to the stator poles. The 90° angle gives the motor its best efficiency.

When a three-phase motor starts, the lines of force from the rotating magnetic field cut the rotor bars at a very high rate. This causes a high-frequency voltage in the rotor bars. This high rate of change in voltage and resulting current give the rotor circuit a high inductive reactance. (The current lags behind the voltage in the rotor circuit.) This lag in current flow makes the rotor's pole form later than the stator's pole does. The stator pole has decreased in power by this time, and the two poles do not react to each other as they do at 90°, and so there is less torque per amp.

As the rotor speed catches up to the speed of the rotating magnetic field, the rotor frequency drops, and the angle improves. At approximately 70 to 80 percent of synchronous speed (synchronous speed is the speed of the rotating magnetic field), the motor will develop maximum torque. If there is no load, the rotor will accelerate to near-synchronous speed. At this speed, few lines of force are cutting the rotor bars, and so there is very little current flowing in the rotor circuit. When there is very little current, the rotor poles will be very weak, and very little torque will develop. The synchronous speed is reached when the rotor and the rotating magnetic field are traveling at the same speed.

At synchronous speed the lines of force flow through the rotor in only one direction. Because of this, the bars are not cut, and no voltage is produced in them. In Figure 3-14a, the lines of force travel from pole 1 to pole 2. By the time the cycle changes, the rotor is aligned with pole 2, so that the lines of force go through the rotor in the same direction, now from pole 2 to pole 1 (see Figure 3-14b).

If the rotor is placed in a dc field and not moved, there will be the same reaction, no current flow in the rotor bars.

When the rotor is loaded down to 2 to 5 percent slip, or 95 to 98 percent of synchronous speed, the current in both the rotor and stator circuits is normal, and the motor will pull its rated load. The percentage of slip = synchronous speed − shaft speed ÷ synchronous speed.

Single-phase motors have a rotating magnetic field created by the offset currents of the start and run windings. This rotating magnetic field brings the rotor up to 70 to 75 percent of synchronous speed, and the start winding is then switched off. The motor will continue to accelerate to its rated speed because of the poles created in the rotor by the lines of force from the run winding. These lines of force from the run winding create a voltage and a current in the rotor in the same way as does any one of the three windings of a three-phase motor. A three-phase motor will continue to run if one phase is opened but will not start on two of its windings. The motor's pulling power will also drop to one-half of its normal rating.

The bars in the rotor of three-phase motors have many variations. The size, the shape, the material they are made of, and the depth they are placed in the rotor's iron all will determine how much current will flow in the rotor circuit. The amount of current flowing in the rotor circuit will establish how much starting, or inrush, current will flow in the stator and the amount of starting torque the motor will have. It will also determine how much slip the motor will have at full load. By varying the design of the rotor bars, the motor can be made for different load requirements. This information is found on the nameplate as the code letter. The code letter designates the locked-rotor KVA per horsepower, according to NEMA standards. All electric motors should perform within these standards.

Preparing the Stator for Stripping. Because the windings are usually hard baked, and some are encapsulated (covered with an epoxy compound for additional protection), it is necessary to soften or char the insulating material. Before doing this, the coil ends opposite the connections should be cut off. Figure 1-52 is one method of doing this using an air chisel. The insulation is charred with a burn-off oven. When insulation is burned off, the temperature should be carefully controlled, or the insulation between the laminations will be destroyed. The temperature should not exceed 700°F. This insulation is used to insulate magnetically the laminations from one another. When this insulation is destroyed, the laminations will heat excessively because of the circulating current between them. As T-frame motors have a minimum amount of iron per horsepower, any loss of insulation will cause them to heat excessively. Heating the stator unevenly or too fast can also warp the laminations. If the winding insulation catches fire, especially that on encapsulated windings, the additional heat can seriously damage the stator. Some ovens are equipped with controls that turn on a fine mist of water to snuff out any flames.

Another method of breaking down the winding insulation is with chemicals. After the windings are cut off, the stator is placed in a special tank. Some types use fumes and others immerse the stator in liquid. Once the insulation has been broken down and the connections are pliable, the data can be accurately recorded.

REWINDING THREE-PHASE MOTORS

There are many steps in rewinding the three-phase motor.

1. Taking data.
2. Stripping the winding.
3. Insulating the stator.
4. Winding the coils.
5. Placing the coils in the slots.
6. Connecting the coils.
7. Testing the winding.
8. Varnishing and baking.

Taking Data. The following information should be recorded: (1) nameplate data, (2) connection, (3) number of turns per coil, (4) wire size, (5) wires in multiple, (6) pitch, (7) coil extension, (8) number of groups, (9) number of poles, (10) number of coils per group, (11) number of slots, and (12) whether the winding is lap or concentric.

All these data must be recorded accurately to enable the repairperson to rewind the stator without loss of time. The following is a chart listing all the important data needed to do this. After "Remarks," such things as length of leads, special insulation, or anything that may be destroyed during the stripping process should be noted.

DATA SHEET FOR POLYPHASE MOTOR

Make	Serial	Cycle		
H.P.	R.P.M.	Volts	Amps	Frame
Temp.	Duty	S.F.	Code	Design
Model	Type	Style	Enclosure	Hz
Efficiency	Power factor	Bearings S1. BB. #		
Connection	Turns	Wire size	Wires in mult.	
Pitch	Coil ext.	No. of groups	No. of poles	
Coils/Group	No. of slots	Lap	Concentric	
Remarks:				

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Layer #1																																				
Layer #2																																				
Layer #3																																				
Layer #4																																				

CONCENTRIC COIL PLACEMENT FOR LAYERED WINDINGS.

A sample data sheet for rewinding three phase motors.

A sample data sheet for rewinding three-phase motors.

NAMEPLATES FOR DUAL-VOLTAGE, THREE-PHASE MOTORS

Figure 3-15 shows a typical nameplate for a three-phase, dual-voltage, wye-connected motor. Note the connections for both high and low voltage. Examination of the nameplate reveals that it is for a 230/460-volt, three-phase, 60 Hz, 10 hp, 1,760 rpm motor. Usually these plates provide a connection diagram for high and low voltage. The connection diagram will also indicate the type of internal connection the motor has. The nameplate should be removed if the stator is going to be burned.

It is important to understand the meaning of some of the terms listed on the nameplate. Some of these terms are *design, code, rating, service factor, insulation class, frame, temperature, efficiency,* and *power factor.*

Design. Polyphase, squirrel-cage, integral-horsepower, induction motors have been designated as being design *A, B, C,* or *D*. These motors are designed to withstand full-voltage starting. Motors with designs *A, B,* and *C* have a slip at a rated load of less than 5 percent. Design *D* motors have a slip at a rated load of 5 percent or more. Design *A* and *B* motors of ten poles or more may have a slip at a rated load of 5 percent or more. The locked rotor and breakdown torques that are developed and the locked rotor currents are related to the design letter. Tables of such value can be found in the NEMA publication, *Motor Standards*. All motors should perform within the standards described in this publication if they meet NEMA standards.

Code. The code letter is the letter that appears on the nameplate of ac motors to show the locked rotor K.V.A. (kilovolt amperes, or 1,000 × volts × amperes) per horsepower. Locked rotor amperes can be computed from tables listing the K.V.A. per horsepower for the different code letters. For example, for the code letter *G*, the K.V.A. per horsepower is 5.6 to 6.3. The K.V.A. input for a ten-horsepower motor exceeds 10 × 6.3 = 63 K.V.A.; that is, watts / volts =

amperes. To find the inrush amperes or the locked rotor amperes for the motor if it is connected for 230 volts, the following method is used: 63 K.V.A. = 63,000 watts, 63,000 / 230 volts = 274 amperes. If the motor is connected for 460 volts, 63,000 / 460 = 137 amperes. This figure is needed to determine the size of overcurrent protection for the circuit and the motor.

Rating. The term *Cont*, or 24 hours, indicates the period of time in which the motor will develop full horsepower at the stated voltage and frequency shown on the nameplate without overheating and exceeding the temperature rise on the nameplate. *Duty* is also a term used for this purpose on some nameplates. Some motors are designed for one-half or one hour of duty.

Service Factor. The service factor of an ac motor is a multiplier that, when applied to the rated horsepower, indicates the permissible horsepower loading that may be carried at the rated voltage, frequency, and temperature. The multiplier 1.15 indicates that the motor may be overloaded to 1.15 times the rated horsepower.

Insulation Class. The insulation class is not on all nameplates; it indicates the temperature class of the complete insulation system inside the motor. Some service centers upgrade all rewound motors to Class F or H. The insulation classes are given in centigrade. To convert centigrade to Fahrenheit, use the formula $F = (9 / 5) \times C° + 32$. The insulation classes are Class A, 105°C; Class E, 120°C (used in Europe); Class B, 130°C; Class F, 155°C; Class H, 180°C; and Class C, 220°C.

Frame. The frame number can be used to determine a motor's measurements. This information is documented in the form of a chart. Some of the measurements found on the charts are the shaft diameter, the distance from the shaft to the base, the spacing of the mounting holes, and the type of mounting. These are NEMA standard measurements, and so all motor manufacturers build motors to these specifications.

Temperature. This is the temperature the motor is allowed to reach under full load and within its *duty* time. It is usually given in degrees centigrade.

Efficiency. Efficiency is a measurement of the total power input divided by the total power output and is expressed as a percentage. To obtain this figure, the electric motor companies select a number of motors, test each of them, and then average the results.

Power Factor. A motor's power factor is the ratio of kilowatt input to the killovolt ampere input. The number is expressed as a percentage. The electric motor manufacturers compute the power factor of a number of motors that are

loaded at a rated load and on a rated voltage. The power factors of all these motors are then averaged. If a factory corrects its power factor, this information can be useful.

A motor's power factor can vary. If a motor is underloaded or the voltage is higher than the motor's rated voltage, the motors power factor will go down. The power factor can be found using a wattmeter, a voltmeter, and an ammeter. After taking each of these readings from the motor, use the formula

$$\frac{\text{Watts}}{\text{Volts} \times \text{Amps}} = \text{Power Factor}$$

The wattmeter gives the actual power being used by the motor. Multiplying the voltmeter reading by the ammeter reading gives in watts the apparent power used by the motor. The difference between the actual power and the apparent power is called wattless power or magnetizing power, and wattless power / applied voltage = the amperes of wattless power or magnetizing amperes.

Correcting the power factor reduces the magnetizing amperes, and so the amperes of the circuit will go down. Reducing the magnetizing amperes of the circuit allows more of the circular mils of the circuit's conductor to be used for the amperes of actual power. Even though the magnetizing amperes are not part of the actual power, the conductor must be large enough to carry both. The result of lowering the magnetizing amperes of a circuit is a higher voltage. If the power company has to correct the power factor, it will charge a penalty.

RECORDING OTHER DATA

After the nameplate information is recorded, the stator should be marked with a chisel where the leads come away from the connection side of the winding. Some stators have more room on the connection side. The first information that is taken from the windings is the connection. In order to recognize these connections, the repairperson must have a basic knowledge of windings and their connections. After recording the connections, measure the coil extension and take the wire size from the cross-connections. The wire size should be noted carefully. A common mistake is to record one size larger. If the wire is not straight or clean, it can appear to be the next size larger. If there are multiple wires (more than one strand coming out of the coil group), check them all as two wire sizes are common. If the wire fits loosely in the wire gauge or measures between sizes with a micrometer, it could be a half-size wire. In this case, the replacement wire should be the larger size if the half-size is not available. Pull out several coils until a complete coil is uncovered. The span or pitch can then be counted. Start with one coil side as one and count each slot up to and including the other coil side, as shown in Figure 3-16. This coil span is 1–8. Next count the turns of a coil and record them. The data sheet is arranged to record the most important

information first. The connection, turns, wire size, pitch, and winding arrangement (lap or concentric) will be destroyed when the stator is stripped. Coil arrangement will be explained under "Three-Phase Concentric Windings" in this chapter.

Stripping the Windings. After the previous information is recorded, the windings can be stripped. Figure 3-17 shows a pair of pliers being used to pull out the wires. Care must be taken not to bend the laminations.

After the wires have been removed, check carefully for sharp burrs, fused copper, and bent stator teeth. Anything that can puncture the slot liner should be removed with a file or chisel.

Insulating the Stator. The stator insulation should be replaced with insulation of the same thickness and as high or a higher temperature rating. Most shops use Class F or Class H paper for all slot-liner insulation. Cuffed insulation of these types is also available in all standard widths and thicknesses. Sheets and rolls are also available. Some shops reenforce the edges of the insulation with glass tape before forming it. Figure 3-18 shows a motor being insulated with cuffed liners. Figures 1-59 and 1-60 are two types of liner formers. It is important that the liners fit the slot exactly. The liner should extend beyond the slot 3/16 inch on small motors and up to 3/8 inch on large motors.

Coil-Group Arrangements in Three-Phase Motors. There are two coil group arrangements for three-phase motors, lap winding and concentric or chain windings. The coils of lap windings (Figure 3-19) all have the same shape, the same span, and the same number of turns. There is the same number of coils as there are slots, and each slot contains two coil sides. Concentric or chain windings (Figure 3-20) can have one, two, three, or more different spans. They can also have a different number of turns per coil, and the slots can contain one or two coil sides. The number of coils can be the same as, one-half as many, or two-thirds as many as the number of slots in the stator.

Coil Types for Lap Windings. There are two types of lap windings, the formed coil and the mush coil. The formed-coil lap winding is usually found in larger motors that range from 50 to thousands of horsepower and are designed for voltages of over 600 volts. The wire in these motors is either square or rectangular. To form the coils, the wire is wound in layers in the shape of a loop or skein, and then the loop is placed in a forming machine that shapes it into a diamond shape. Figures 3-21 and 3-22 show these two machines. The shaped coils are then taped (as shown in Figure 3-23), after which they are dipped in varnish and baked. The coils are then inserted in the stator. Stators that are wound with formed coils have open slots, as pictured in Figure 3-24a. The coils are connected into groups, and the groups are then connected as wye or delta. Some companies specialize in making formed coils for shops that do not have forming equipment.

The mush coil is used in motors of up to 300 horsepower that operate on voltages below 600 volts. The coils are shaped on a winding head and are made with round wire. The wire is not layered, as with formed coils, but is guided at random into the grooves of the winding head. The mush coils are sometimes called *random-wound coils.* The coils are wound in groups with the wire(s) crossing over from coil to coil without being cut. Stators using the mush coil usually have semiclosed slots, as seen in Figure 3-24b.

It is common to have to feed the wires of mush coils into the slots one at a time. Figure 3-25 shows how to insert a coil. There are several types of winding heads available to form mush coils. The heads shown in Figures 3-26 and 3-27 can form diamond- or rectangle-shaped coils. The head in Figure 3-28 forms coils with rounded ends. This round form comes in several widths. After selecting the form with the right width, only the length adjustment needs to be made. Another type has enough slots to wind a complete phase for a four-pole motor without cutting the wire. This one is called a *continuous head,* and with it there is no need to make group-to-group connections. Figure 3-29 shows a winding head with the coils wound on it and also a group removed from the head. This is a diamond-shaped group. Figure 3-30 shows a lap-wound stator with diamond-shaped coils. If the stator were cut apart and the slot assembly flattened, it would look like that shown in Figure 3-31. Note the coil-to-coil cross-connections; they are drawn in for illustration purposes but would not show in an actual winding. The number of coils per group depends on the number of poles and the number of slots. This will be explained in ''Odd-Pole Grouping'' in this chapter.

Winding the Coils. After the slot liners are in place, the measurement for the new coil setting is made. A single wire can be formed in the shape of the old coil by threading it through the slots of the proper span and shaping the ends. The coil should extend beyond the slot liner about 3/8 to 1/2 of an inch, as illustrated in Figure 3-32. This is done so that the phase insulation paper (explained later).will stay in place easily. The point or nose of the coil is shaped according to how much end room is available. The pattern is shaped to fit from the bottom of the slot on one side to the top of the slot on the other side. The point of the coil will assume a shape during the winding that will allow it to fit the rest of the coils without difficulty. If the point is not long enough, the coils of the winding will ''stack,'' and the winder will have difficulty inserting the coils and later shaping them. If the point is too long, it can touch the end bell and cause a ground. The pattern wire is the size of the smallest part of the coil. The number of turns and the size of the wire will determine the size of the outside or largest part of the coil.

Remove the pattern wire from the stator and place it on the winding head. Expand the head to fit the pattern wire tightly, and then remove the pattern wire and fit it into the slots again to see whether it has the right shape. Several turns of wire can be wound around the winding head for this pattern coil if preferred. If the pattern is satisfactory, a coil group can be wound.

The coils of small motors may be wound into a rectangular form and then the two sides shaped into a rounded or diamond form by pulling at the center of the opposite sides, as shown in Figure 3-33. This forms a four-sided coil of two straight sides for the slots and two rounded sides on the ends. This type of coil takes up less end room.

GROUP WINDING. Most three-phase motors, with the exception of very large ones with formed windings, use coils wound in groups. The number of coils in each group depends on the number of slots and the number of poles, as described under "Connecting the Three-Phase, Lap-wound Motor." This practice is called *group* or *gang winding*. In group winding, several coils are wound before the wire is cut, as shown in Figure 3-34.

Placing the Coils in Slots. The turns of the coils are inserted one by one into semiclosed slots. Use the following procedure: Spread or fan out the turns on one side of the coil, and hold the coil at an angle so that all the turns can be fed into the slot. Figure 3-35a shows this procedure. Make sure that each turn is placed inside the insulation. Sometimes the wires are placed by mistake, between the insulation and the iron core, and a ground results.

Pull the side of the coil through the slot until all the turns are in the slot. The other side of the coil remains free, as shown in Figure 3-36. Note that a coil side occupies half a slot. Many winders prefer to hold the coil over the entire length of the slot and drop the turns directly into the slots one at a time, as shown in Figure 3-35b.

Continue by placing one side of the second coil in the slot beyond the first, as shown in Figure 3-37. The following coils are fitted in the same manner until the slots of a complete coil pitch hold one side of each coil. The second side of each coil is left out until the bottom half of a slot is occupied by a coil side. The second side of each coil is then fitted on top of the first side of a coil several slots away, according to the pitch of the coil. When coils are wound in groups, the winder always works with a complete group of coils at a time, placing them into the slots, as explained above and illustrated in Figure 3-38.

In this method, one side of each coil is in the bottom half of a slot, and the other side of the coil is in the top half of another slot several slots away, depending on the pitch of the coil. The number of coils of which the top side is left out is usually one or two more than the coil pitch, and they are not put into slots until the stator is nearly completed. Make certain that each coil side extends beyond the slot at both ends and does not press against the iron core at the corners.

Before inserting the second side of each coil, it is necessary to insulate it from the coil already in the slot. This is because each group belongs to a different phase. The voltage between groups is very high.

To insulate between the coil sides in the same slot, follow the procedure given in Figure 3-39 for both open and semiclosed slots. A creased separator or insulation of the proper width and thickness (usually 0.010 to 0.015 in.) is used to

insulate between the top and bottom coil sides in the slot. Slide a separator over the bottom sides of the coil in the slot before installing the top side. It should extend about 1/2 in. beyond the slot liner. When the top side is placed into the slot, slip a formed fiber wedge (round or square) over the top coil. This should extend about an 1/8 in. beyond the slot liner. As each group of coils is placed in the slots, put phase insulation between groups. Varnished glass is used for this purpose. Phase insulation between groups is shown in Figure 3-40. Heavy separators are placed between the coils in the slot and the U-shaped insulators over the top coils. Slot wedges are inserted to hold the coils securely in place. Note also that coils are wound with three wires in parallel.

If there is a large span, as with a two-pole motor, the complete coils may be placed in the slot, starting with the first coil. Use the same insulating procedure as described above for this method.

CONNECTING THREE-PHASE, LAP-WOUND MOTORS

In the following discussion, we shall assume a 36-coil, four-pole, lap-wound, three-phase motor.

All three-phase motors are wound with a number of coils, usually as many coils as slots. These coils are so connected as to produce three separate windings called *phases,* each of which must have the same number of coils. The number of coils in each phase must be one-third the total number of coils in the stator.

Therefore, if a three-phase motor has 36 coils, each phase will have 12 coils. These phases are usually called *phase A, phase B,* and *phase C.*

RULE 1. To find the number of coils in each phase, divide the total number of coils in the motor by the number of phases.

EXAMPLE:

$$\frac{36 \text{ coils}}{3 \text{ phases}} = 12 \text{ coils per phase}$$

All three-phase motors have their phases arranged in either a *wye* (Y) connection or a *delta* (Δ) connection.

A wye-connected three-phase motor is one in which the ends of each phase are joined together. The beginning of each phase is connected to the line. Figure 3-41 shows the wye connection. Because of the pattern formed by the phases in the diagram, this circuit is also called a *Y* (wye) *connection* (actually an inverted Y). Henceforth, *wye* (Y) will be used to describe this connection.

A *delta* connection is one in which the end of each phase is connected to the beginning of the next phase. Figure 3-42 shows the end of the *A* phase connected to the beginning of the *B* phase. The end of the *B* phase is connected to the beginning of the *C* phase, and the end of the *C* phase is connected to the beginning of the *A* phase. At each connection, a wire is brought out to the line. Another way is to connect the end of *A* to the beginning of *C*, the end of *C* to the beginning of *B*, and the end of *B* to the beginning of *A*.

Poles. In the motor under discussion, the coils are connected to produce four poles. Thus, in a 36-coil, four-pole motor, each pole consists of nine coils, as shown schematically in Figure 3-43.

RULE 2. To find the number of coils in each pole, divide the total number of coils by the number of poles.

EXAMPLE:

$$\frac{36 \text{ coils}}{4 \text{ poles}} = 9 \text{ coils per pole}$$

To the eye, the coils appear as shown in Figure 3-44. To simplify the connection process, each coil can be eliminated from the drawing so that only two leads of the coil are shown. Figure 3-45 is such a simplified drawing.

Group. A group is a definite number of adjacent coils connected in series. In all three-phase motors there are always three groups in each pole, one from each phase. Thus, one group is from phase *A*, another group from phase *B*, and a third group from phase *C*.

Therefore, if a pole has nine coils, there must be three coils in each group. This section of three coils is often called a *pole-phase group* or *polegroup*. Three groups in one pole are shown in Figure 3-46.

The coils of any one group are always connected in series, illustrated in Figure 3-47. Here the end of coil *1* is connected to the beginning of coil *2*. Likewise, the end of coil *2* is connected to the beginning of coil *3*. The beginning of coil *1* and the end of coil *3* are coil-group leads for connection to other groups. Another view of the same connection is shown in Figure 3-48a.

Coils are connected into a group when they are individually wound. When coils are group wound, the groups are automatically formed by the method of winding, as shown in Figures 3-48a and 3-48b. Most motors are group wound.

RULE 3. A simple way to determine the number of groups is to multiply the number of poles by the number of phases. For example, in the motor being discussed, 4 poles × 3 phases = 12 groups, or *groups* = *poles* × *phases*.

If the number of groups is known, it is easy to determine the number of coils in each group.

RULE 4. The number of coils in each group is equal to the total number of coils in the motor divided by the number of groups:

$$\text{Coils per group} = \frac{\text{total number coils}}{\text{number of groups}} = \frac{36}{12} = 3$$

When a three-phase motor is to be connected, the number of groups is first determined, and then the coils per group are computed. For example, a six-pole, 54-coil, three-phase motor has 3 phases × 6 poles, or 18 groups. Then, 54 coils ÷ 18 groups equals 3 coils per group.

Wye Connection. The windings of the motor can now be connected. Assume a 36-slot, four-pole, wye-connected motor. The procedure is as follows:

1. There are three coils in each group, and the coils in each group are connected in series when the group is wound. This is shown in Figure 3-49.
2. Connect the groups of the *A* phase together, as shown in Figure 3-50. The groups must be connected so that the current will flow through the first *A* group in a clockwise direction and through the second *A* group in a counterclockwise direction, and so on. This will produce alternate north and south poles.

   The beginning of the *A* phase is spliced to a flexible lead wire and brought out of the motor. The end of the *A* phase is connected later to the ends of the *B* and *C* phases and insulated.
3. Connect the *C* phase exactly like the *A* phase. To simplify connections, skip phase *B*. The connections of phase *C* are shown in Figure 3-51.
4. Connect phase *B* in the same manner as phases *A* and *C* were connected. Figure 3-52 shows that the start of phase *B* begins at the fifth group. This type of connection, in which a group is skipped in order that connection of the next phase can be started, is called a *skip-group connection.* In Figure 3-52, the arrows under each group point in opposite directions; that is, the first arrow indicates clockwise; the second arrow, counterclockwise; the third, clockwise; the fourth, counterclockwise. This is one method of checking connections for the correct polarity of groups. To simplify these diagrams, each group can be shown as a rectangle, as shown in Figure 3-53, which is a straight-line diagram.

As stated earlier in this chapter, the three-phase winding consists of three single-phase windings. In Figures 3-53a and 3-53b, the *A* phase and the *C* phase are connected exactly like the single-phase run winding illustrated in Figure 1-54b. The *B* phase has to be the opposite polarity of the *A* and *C* phases. This is accomplished by skipping the first *B* phase group and starting the connection at the second *B* phase group, as in Figure 3-53c. Figure 3-53d shows the result of putting all three phases together in a straight line. The same circuitry rules apply

to each phase of a three-phase winding as apply to a single-phase winding. A four-pole winding can be connected in one, two, and four, one and two, and two and four circuits.

Figures 3-54a, b, c, and d show a circular diagram made in the same sequence. First the *A* phase, the *C* phase, and the *B* phase and then all three phases are put together in a circular diagram. Note the small number next to each group. This number shows the position the group has in the circular diagram. The number and position of the groups can be compared with the straight-line diagram in Figure 3-53d.

In these diagrams, the arrows on the line leads all point in the same direction. Actually the current at one moment flows in one line lead and out of the other two, and the next moment in two lines and out of one. To be certain of correct connections, the arrows will be shown pointed inward. In all of the diagrams just presented, the *B* phase, or middle phase, has the arrow drawn in the opposite direction from the two other phases. This provides a check for correct connections of three-phase motors.

A schematic diagram of a three-phase, four-pole, series-wye (1Y) motor is shown in Figure 3-55. In this diagram, each phase consists of four groups, which determine the number of poles in the motor. If there are four groups in each phase, it is a four-pole motor, except when the consequent pole is used. By looking at the schematic diagram, it is possible to tell the number of poles in the motor by counting the number of groups in any phase.

The wye point indicates that it is a wye-connected motor. The diagram also shows that the groups in a phase are connected in series. Therefore, the schematic diagram indicates that the motor is a three-phase, four-pole, series-wye (1Y) connection.

Delta Connection. The same motor will next be connected as a four-pole, series-delta–connected motor. A better understanding of this connection may be gained if the schematic diagram of Figure 3-56 is studied before the connections are made. This diagram shows that the groups are connected in series and, because there are four groups in each phase, that it is a four-pole motor. Because it has no wye point and is connected by joining the end of the *A* phase to the beginning of the *C* phase, and so on, it is delta connected. Thus, this is a three-phase, four-pole, series-delta (1Δ) connection. Note: Each phase in the schematic diagrams is 120° from the other.

Because this is a three-phase, four-pole motor, it will have 3 phases × 4 poles = 12 groups of three coils each. It is not necessary to show the individual coils, as these were shown in the wye connected diagrams. Each group has three coils connected in series. It is a good policy, when making these diagrams, to mark each group with its phase letter and an arrow to show polarity. It is also helpful to color each phase group and the connections of each phase a different color.

The next step is to connect the groups of the *A* phase for proper polarity, as shown in Figure 3-57a. Show the first arrow clockwise, the second arrow counterclockwise, the third arrow clockwise, and the fourth arrow counterclockwise.

1. Connect phase *A* in the same manner as in the wye connection.
2. Connect the phase *C* for proper polarity, as shown in Figure 3-57b. The groups are connected so that the current flows into the groups in the direction of the arrows. Connect the end of *A* phase to the start of *C* phase. To check the polarity, see that all arrows indicating line leads are in the same direction.
3. Continue by connecting the end of phase *C* to the beginning of phase *B*.

The *B* phase is started at the fifth group or at the second *B* phase group from the starting point, as shown in Figure 3-57c. In Figure 3-57d, all three phases are put together to form a complete diagram. The end of the *A* phase is fastened to the start of the *C* phase, the end of the *C* phase to the start of the *B* phase, and the end of the *B* phase to the start of the *A* phase.

Because the coil groups are located in a circle in a motor, Figures 3-58a, b, c, and d show how a straight-line diagram is made into a circular diagram. The diagram of Figure 3-58d shows their true position in the motor.

The procedure in connecting either a wye or delta motor is the same except for the point at which the ends of the phases are connected. For a wye connection, the ends of each phase are connected together for a wye point; for a delta connection, the ends of each phase are connected to the beginning of another phase.

The wye and delta connections shown so far have been connected in accordance with the skip-group method. It is permissible to connect these motors without skipping a group. Figure 3-59 shows a wye connection in which phases *A*,*B*, and *C* are connected in that order.

Although this connection is just as effective as the skip-group connection, many winders and repairpersons prefer the latter for ease in connecting.

Parallel Connections. Many three-phase motors are designed so that each phase has two circuits or two paths for the current to travel. These are called *two-circuit*, or *two-parallel*, connections. For comparison, the schematic diagrams of a series-wye (1Y) and a two-parallel wye (2Y) connection are given in Figures 3-60 and 3-61. The parallel connection of the groups in each phase provides two paths for the current to follow.

Phase *A* of the two-parallel wye (2Y) connection diagram with rectangles is illustrated, with the groups indicated, in Figure 3-62a. Begin by connecting one line wire to groups *1* and *3* of the *A* phase. Continue as shown in the diagram. After connecting phase *A*, connect phase *C*, as shown in Figure 3-62b. Next connect the *B* phase, as in Figure 3-62c. Each wye must contain one end of each phase. Figure 3-62d shows a complete diagram of a three-phase, four-pole, two-parallel wye connection. Figure 3-63 shows a circular diagram of the same motor.

How to Recognize a Connection. It was pointed out previously that determining the connections on a three-phase motor when stripping it is important and requires a knowledge of connections. A simple method of taking connection data requires that the winder or repairperson visualize the schematic diagram of each type of motor.

It is important at this point to take several precautionary measures that may be helpful in recognizing these connections. Do not cut or remove any wires or leads from the winding until you are certain of the connection. Read and record the nameplate data. This will usually tell you if the motor is wound and connected for single or two speed, single voltage or dual voltage, and sometimes wye or delta. The speed is always recorded on the nameplate, and because the speed depends on the number of poles, it is simple to find the number of poles: Just divide 7,200 by the speed for a 60 Hz motor. Remember also that the number of groups in each phase is equal to the number of poles. If the motor is connected for two voltages (dual voltage), nine leads are brought out and these may be connected in series or in parallel and as wye or delta, as explained in the section "Connecting a Two-Voltage Wye Motor" (page 112). If the motor is a two-speed motor, only six leads may be brought out. Thus, if the schematic diagram of the above motors is mentally pictured, little trouble should be encountered in determining the connection. With this in mind, proceed as follows.

First, trace out a line lead to the winding and count the number of groups or coils that each line or terminal lead connects to. Refer to Figure 3-64 and note that each line lead connects to just one group. Figure 3-64 is a schematic and Figure 3-65 is a diagram of a two-pole, series-wye or 1Y-connected motor, probably the simplest of all three-phase motors. Look at Figure 3-66, a four-pole series-wye or 1Y and note again that each line lead still connects to just one group. Consequently, if a line lead connects to just one group, the connection must be a series-wye. This is the only three-phase motor in which all terminal leads connect to only one group. The only difference between these two motors is in the number of pole groups. A two-pole motor will normally have 2 poles × 3 phases = 6 groups (two in each phase); a four-pole motor will normally have 4 poles × 3 phases = 12 groups (four in each phase); and so on. The number of groups can always be obtained from the nameplate speed and sometimes by actual count. It should be remembered that schematics for recognizing connections do not have to take into consideration the number of poles; this information can be obtained from the nameplate. The important points are type of connection (wye or delta) and the number of circuits (1Y, 2Y, 1Δ, 2Δ, and so on).

If each line lead connects to two groups, it can be assumed that the connection is either series-delta (1Δ) or two-parallel wye (2Y). Both circuits are shown in Figure 3-67. To identify the two-parallel wye connection, look for a wye connection in which six groups are joined. If this cannot be found, the connection must be series-delta. Sometimes two separate wye points of three groups each will be found, as in Figure 3-67b.

If each line lead connects to three groups, as shown in Figure 3-68, the motor can only be a three-parallel wye (3Y) type. No other type has such a connection. If each line lead connects to four groups, as shown in the two circuits of Figures 3-69a and b, the motor may be either a two-parallel delta (2Δ) or a four-parallel wye (4Y). Identification of the four-parallel wye (4Y) is then indicated by the connection of twelve groups at the wye point or four separate wye connections. These examples show that if the schematic diagram is visualized, the type of connection can easily be determined.

To determine the number of poles, several different methods may be used. If the speed of the motor is known, the number of poles is easily found, as the speed of a three-phase motor bears a definite relationship to the number of poles. This was explained in Chapter 1. Thus, if the speed marked on the nameplate is 1,725 rpm, it is a four-pole motor; if 1,150, it is a six-pole motor, and so on.

Another method of determining the number of poles is to count the number of groups and divide by the number of phases. For instance, if 12 groups are found, divide 12 by three phases, and the result is four poles. The groups are easily recognized because each group has two jumper leads.

Another method is to count the number of jumpers. For instance, if it is found that a motor has a two-parallel wye connection and there are six jumpers, this indicates that it is a four-pole motor, and it is connected as shown in Figure 3-70. In this illustration, the numbers indicate the jumpers.

Sometimes it is hard to identify the groups when a winding is charred from the burn-off oven. In this case, an easy way to identify the number of groups is to count the group ends. This includes the ends fastened to the leads and the ones that are joined in wye connections. Divide this number by two (two ends per group) to obtain the number of groups. Divide the number of groups by the number of phases (three) to obtain the number of poles. It is common for motors to burn off some of the group ends when they burn out. The number of groups in a three-phase motor will always be divisible by six. Each phase will always have a pair of poles, never one or three, and each will have the same number of poles. Therefore, two poles (per phase) times the phases (three) equals six groups. There would never be ten or 11 groups in a four-pole, lap-wound, three-phase motor.

The span of the coils is another way of determining the number of a motor's poles. The approximate span is found using the formula (slots / poles) $+ 1 \times 0.8 =$ span. A four-pole, 36-slot motor can have a 1–7, 1–8, or 1–9 span, depending on the manufacturer's design. Full span or pitch is found using the formula (slots / poles) $+ 1 =$ full span. The span of most motors is 80 percent of full span.

Connecting Three-phase Motors for Two Voltages. Most small- and medium-sized three-phase motors are made so that they can be connected for either of two voltages. The purpose in making motors for two voltages is to enable the same motor to be used in localities that have different power-line voltages.

Usually the leads external to the motor are connected to provide a series connection for the higher voltage and a two parallel connection for the lower voltage.

Figure 3-71 shows four coils that, if connected in series, may be used on a 460-volt, ac power supply. Each coil receives 115 volts. If the four coils are connected in two parallel to a 230-volt line, as shown in Figure 3-72, each coil still will receive 115 volts. A third method of connection of the four coils is given in Figure 3-73. This is a four-parallel connection for a 115-volt operation of the motor. Each coil still receives 115 volts. Thus, regardless of the line voltage, the coil voltage is the same. This is the principle used in all two-voltage machines. Therefore, if four leads are brought out of a single-phase motor designed for 460- and 230-volt operation, it can be readily connected for either voltage. Figure 3-74 shows the series connection for 460 volts, and Figure 3-75 gives the parallel circuit for 230 volts.

This principle of voltage dividing between the coils is applied to a three-phase, four-pole, wye-connected motor in Figure 3-76. This motor is a series-connected wye for 460-volt use. If it is used on a 230-volt line, it will be connected for two parallel, as shown in Figure 3-77. An alternative connection using two wye points is shown in Figure 3-78. Both diagrams are correct.

Connecting a Two-Voltage (Dual-Voltage) Wye Motor. Practically all three-phase, dual-voltage motors have nine leads brought out of the motor from the winding. These are marked T_1 through T_9, so that they may be connected externally for either of two voltages. These are standard terminal markings and are shown in Figure 3-79 for wye-connected motors. There are four circuits in this motor—three circuits of two terminals and one circuit of three terminals. This information will be used later for testing.

An easy way to determine the numbering system of a wye or delta schematic is the spiral method as shown in Figure 3-80a. Starting at T_1, draw a line through T_2 and T_3. Then drop down to the next lead of the A phase, T_4, and go through T_5 and T_6. Continue on to the third lead of the A phase and complete the spiral from T_7 through T_8 and T_9. Figure 3-80b shows how the numbering is done with a delta schematic. Note that each phase has a two-section winding so that these sections may be connected in series for the higher voltage and in parallel for the lower voltage. To connect for the high voltage, connect groups in series, as shown in Figure 3-81. Use the following procedure: Connect leads T_6 and T_9, and tape; connect leads T_4 and T_7 and tape; connect leads T_5 and T_8, and tape; and connect leads T_1, T_2, and T_3 to the three-phase line.

To connect this same motor for the low voltage, the groups are connected in two parallel, as shown in Figure 3-82. Use the following procedure: Connect lead T_7 to T_1 and to line lead L_1; connect lead T_8 to T_2 and to line lead L_2; connect lead T_3 to T_9 and line lead L_3; and connect T_4, T_5, and T_6 together to form an external wye.

Figure 3-83 is a straight-line diagram of a two-voltage, four-pole, wye-connected motor that is connected as explained for the motor shown in Figure 3-81.

Figure 3-84 shows a circular diagram of a three-phase, dual-voltage, wye-connected motor.

Connecting a Two-Voltage Delta Motor. Refer to Figure 3-85 for the standard terminal markings of a dual-voltage, delta-connected motor. Note that a dual-voltage, delta-connected motor has three circuits of three terminals each. Figure 3-86 shows a schematic diagram for both high- and low-voltage connections. For a high-voltage operation: Connect lead T_4 to T_7; connect lead T_5 to T_8; connect lead T_6 to T_9; and connect leads T_1, T_2, and T_3 to L_1, L_2, and L_3, respectively. For a low-voltage operation: Connect leads T_1, T_7, and T_6 to the line lead L_1; connect leads T_2, T_4, and T_8 to line lead L_2; and connect leads T_3, T_5, and T_9 to line lead L_3.

A straight-line diagram of a two-voltage, four-pole, delta-connected motor is shown in Figure 3-87 and is connected for the higher voltage.

Wye-Delta, Dual-Voltage. Some motors are designed so that they may be connected in delta for low voltage and in wye for high voltage. The voltage ratio between high and low should be $\sqrt{3}$ to 1. Figure 3-88 shows the terminal markings for this type of motor. Note that six leads are brought out of the motor, two from each phase.

This connection is also used for starting large motors or, with smaller motors, when reduced torque on starting is needed. The motor is started with a controller that connects the windings as wye for starting. It is then switched to delta for running. There is less inrush current when the motor starts on the wye connection. When there is less current, there is also less torque. The motor has full power when the controller connects its windings as delta for running. Any delta-connected motor can be converted to a wye-delta. The end of each phase is disconnected from its respective line; a lead is put on it; and it is brought out of the motor. The control will be explained later in Chapter 4.

The voltage ratio between wye and delta is $\sqrt{3}$, or 1.73. This means that if a wye-connected motor is mistakenly connected delta, the windings would receive 1.73 times as much voltage as they are designed for. The motor would draw excessive amperes and soon burn out.

If a delta-connected motor were mistakenly connected wye, the windings would receive voltage applied divided by 1.73, or times 0.58. A fifty-eight percent reduction in voltage would cause the motor to have much less power than its rating and the amperes at no load would be very low.

Short Jumper Connections

All of the diagrams that have been shown thus far have been made with short jumper connections, in which the end of a group is connected to the end of the adjacent group of the same phase, in other words, an end-to-end or a beginning-to-beginning connection, as shown in Figure 3-83. These are also known as top-to-top, right-to-right, and short throw connections.

The short jumper connection is sometimes made with the *B* phase arranged as in Figure 3-89a. The first coil group of the *B* phase is skipped as before, but from the second coil group, the connection is made back to the first coil group instead of the third group. The left lead of the fourth *B* phase coil group is called T_9, and the right lead of the fourth group connects to the right lead of the third coil group. The left lead of the third coil group is the end of the phase. Figure 3-89b is a complete straight-line diagram of a one- and two-wye, four-pole, short jumper motor connected in this way. The diagram appears split in half, with the T_1 through T_6 leads in one half, and the T_7, T_8, and T_9 leads with the internal wye contained in the other half. Figure 3-90 is a circular diagram of this one- and two-wye connection. A motor connected in this way looks much different from a motor connected as in Figure 3-84, but electrically is no different.

The two-pole motor can be connected in seven different ways: one wye, two wye, one and two wye, wye-delta, one delta, two delta, and one and two delta. Figure 3-91a, b, c, d, e, and f show all but the one-wye connection; the one-wye diagram is in Figure 3-65.

The two coil groups of each phase in a two-pole motor are considered to be adjacent and must be of opposite polarity. The span of each coil group of a two-pole motor will cover one-half of the stator's circumference. Two-pole motors do not have as much starting torque as do the slower-speed motors of the same horsepower.

The four-pole, short jumper connections illustrated so far are one wye, two wye, one and two wye, wye-delta, one delta, one and two delta, and one and two wye split. Some other connections are four wye (Figure 3-92a), two and four wye (Figure 3-92b), four delta (Figure 3-92c), and two and four delta (Figure 3-92d). Figure 3-92e is a one-wye connection with the *B* phase reversed by starting it at the opposite end.

A good way to learn three-phase connections is to draw each one in color. First draw each phase separately and then combine them into one drawing. Place an arrow next to each pole to show its polarity, and then follow the following six rules:

1. Adjacent poles must be of opposite polarity (with the exception of consequent pole).
2. Phase *B* is connected to have the opposite polarity of phases *A* and *C*.
3. Each phase must have the same number of coil groups.
4. Each circuit must have the same number of coil groups and turns.
5. The number of circuits possible will be any number that will divide evenly into the number of pole groups. For example, a six-pole motor can have one, two, three, or six circuits.
6. The lead numbers can be found by using the spiral method described in Figures 3-80a and b for dual voltage.

Long Jumper Connections

Long jumper connections are those connecting the end of the first group to the beginning of the third group of the same phase, as shown in Figure 3-93a. These

are also called top-to-bottom, right-to-left, and long throw connections. Figure 3-93b shows the B phase, and Figure 3-93c shows the C phase. Like the short jumper connection, skipping the first B phase coil group and starting at the second coil group will reverse the B phase. Figure 3-94 shows all three phases in a straight-line diagram. This is called a four-pole, one-wye, long jumper connection. Figure 3-95a is a two-wye; Figure 3-95b is a one- and two-wye; Figure 3-95c is a two- and four-wye; and Figure 3-95d is a wye-delta connection. Figure 3-96a is a one-delta; Figure 3-96b is a two-delta; Figure 3-96c is a one- and two-delta; and Figure 3-96d is a two- and four-delta connection. The long jumper connections have like poles connected in sequence or in the same circuit as in the two and four circuit motors. Short jumper connections have adjacent or opposite polarity poles connected in sequence or in the same circuit.

The long jumper and short jumper connections make no difference in a motor's power or starting ability. When a motor is started using the part-winding-start method (explained later), the short jumper connection will make more noise than will the long jumper connection.

A two-circuit motor will have better ampere distribution between circuits connected long jumper if the motor has an uneven air gap between the stator and rotor. A coil group located next to a large air gap will draw more amperes than will a coil group located next to a small air gap. Putting the two groups in series will equalize the amperes.

If a motor has an odd-pole grouping (explained later under "Odd-Pole Grouping"), it may not be possible to use a long jumper if there is more than one circuit. All two-speed consequent-pole motors are connected on long jumper.

In conclusion, it is necessary to be able to recognize and to make both long and short jumper connections. Some repair shops rewind all motors in exactly the way they were wound originally, which is probably the safest procedure for rewinding motors.

THREE-PHASE CONCENTRIC WINDINGS

The concentric method of forming three-phase coils has been used for a long time; patents on them date back to the late 1800s. The reason for the return to this type of winding is that the concentric coil can be wound into the stator by machine, thereby cutting down on the manufacturing cost. The lap winding can be inserted only by hand and is in most cases more efficient. The many variations of the concentric windings are a result of the manufacturers' attempting to improve their performance.

The concentric windings have many variations compared with the lap winding. The coils of a lap winding all have the same shape, turns, and span, and the slots all contain two coil sides. There is also the same number of coils as there are slots. With the concentric winding, the coils in a group will not have the same pitch as with lap windings. The slots may contain either one or two coil sides. There can also be a different number of turns in the coils of a group.

One of the many variations used in the concentric winding method is the four-pole, 36-slot diagram shown in Figure 3-97. Concentric windings are placed in the stator in layers, which makes the connecting sequence look different from the lap winding. Figure 3-97 is a three-layer winding. Each layer is a complete phase, and the coils of each group do not share the slots with any other coils.

It is important to record the slot location for each coil group when taking data before stripping a concentric winding. One method of illustrating concentric windings is shown in Figure 3-98. The 36 slots shown in this diagram are separated into four layers. This method makes recording and understanding the winding sequence easier than a circular drawing does. To illustrate this winding, the second and third layers must go off the diagram on the right and back on on the left showing their location with respect to the slots.

The motor illustrated in Figure 3-99 is wound in four layers of three groups. The outer layer consists of three groups, and each group has one coil. The next two layers contain three groups per layer, and there are two coils per group. The final layer contains three groups with one coil per group. Figure 3-100 is a straight-line version of this winding. When Figure 3-100 is compared with Figure 3-98, it can be seen that the coils occupy the same slots in both drawings. Only the coil ends are different, and this is because of the sequence in which the coils were inserted. Electrically, there is little difference between the two sequences of insertion. Rewinding this motor in three layers, as shown in Figure 3-98, is easier.

Some of the standard concentric patterns for 36-slot stators are

1. Two coils per group with the outside coils of the group sharing the slots with the other phase, as shown in Figure 3-101. The outside coil span is 1–10, and the inside coil span is 1–8. The outside coil will have one-half as many turns as the inside coil will.
2. Two coils per group with the inside coils of the group sharing the slots with the inside coils of other phases, as shown in Figure 3-102. This group will have an outside coil span of 1–9 and an inside coil span of 1–7. There will be one-half as many turns in the inside coil as there are in the outside coil.
3. Two per group, skipping one slot on either side of the outside coil. The span of the outer coil is 1–8, and the span of the inside coil is 1–4, as shown in Figure 3-103. The inside coil will share the slot with the inside coils of other phases and will have one-half as many turns as will the outside coil of its group.
4. Three coils per group, all sharing the slots with other phases. The span will be 1–9, 1–7, and 1–5, as shown in Figure 3-104. Each coil will have a different number of turns, with the outer coil having the most and the inside coil having the least. This is one of the more efficient concentric winding designs. The turns should be counted very carefully.
5. The consequent-pole concentric winding is shown in Figures 3-105 and 3-106. This winding has six coil groups containing three coils per group. The span is 1–12, 1–10, and 1–8. The coils do not share the slots, and all contain the

same number of turns. There are two coil groups in each phase and they are located opposite each other. All the coil groups are connected for the same polarity. Figures 3-107a, b, c, d, e, and f show all the connections for this motor. The consequent-pole motor is explained in both Chapter 1 and also later in this chapter.

6. Concentric windings designed for a part-winding start. This design splits each coil group into two parts, as illustrated in Figure 3-108. In any of the previously described winding designs, the coils can be split into halves. One-half of the coil group is inserted and insulated, and the other half is then inserted and insulated from the other phases. There are now two circuits in the coil group. Figure 3-109 shows how the connections are made for a two-wye, part-winding-start motor. Part-winding starts will be explained later in this chapter.

Connecting the Concentric Winding

The concentric winding looks different from the lap winding, as mentioned previously. A simple procedure for connecting the concentric winding is as follows. Start the connections with a group in the outer layer at the six o'clock position and proceed in a counterclockwise direction. The left lead of this group will be T_1. Connect this group to the rest of the groups of the outside layer as the A phase, leaving the end of the phase for the wye connection, as shown in Figure 3-110a. Next locate the group that lies 120° to the right of the first coil in the first coil group that was labeled T_1. Tag the left lead as T_3 and connect this group to the rest of the groups of this layer, as shown in Figure 3-110b, leaving the last lead for the wye connection. Locate the coil group in the last layer that is 120° to the right of the first coil of the group labeled T_3 and tag the left lead of this group as T_2. Connect this group as shown in Figure 3-110c to the rest of the groups of this layer, and join the ends of all groups for the wye connection.

The phases of concentric windings may be separated into two or more circuits for dual voltage. Each circuit must have the same number of coils and turns. The method described for the part-winding start can also be made into dual voltage. Figure 3-111 shows a one- and two-coil-per-group winding connected in one and two wye, and Figure 3-112 is a split winding also connected for dual voltage, one and two wye.

When concentric windings do not have the coil groups of the same phase in the same layer, it is necessary to identify all the groups of the same phase before starting the connecting process. This can be done with a marking pen or different colored sleevings. This method of identification can also be used with lap windings to make each phase easy to see.

How to Recognize a Connection

The windings must be loosened by burning or with chemicals in order to determine the connection. Separate the connections and the coil groups so that they

may be counted. If the stator has previously been wound with a continuous winding head, as pictured in Figure 3-113, the group-to-group connections will not be welded and will be hard to find. With this winding head, the whole phase is wound without cutting the wire. The jumper can go from one group to the next on either side of the stator.

Count the number of leads coming out of the winding. Nine leads mean dual voltage and can be in wye or delta. If a nine-lead motor is connected in delta, there will be two times as many coil groups connected to T_1, T_2, and T_3 as there are to the other six leads. Figure 3-114a shows a one- and two-delta connection with two coil groups connected to T_1, T_2, and T_3 and one coil group each for the rest of the leads. Figure 3-114b has four coil groups connected to T_1, T_2, and T_3. Each of the remaining six leads has two coil groups connected to them. This is a two- and four-delta connection.

A wye-connected motor will have as many coil groups connected to each lead as there are wye connections. A wye consists of one coil-group end from each phase. There will be three coil-group ends for each wye. If there is more than one wye connected internally, they may be connected together or separately. Figure 3-115a shows a one- and two-wye connection, and Figure 3-115b shows a two- and four-wye connection. There are two coil group ends connected to each of the nine leads in Figure 3-115b. When there is more than one wye, the coil-group ends of each wye are sometimes connected to a common wire. The common-wire method is much less bulky than a cluster of six or more group ends.

Other things to look for are long jumper, short jumper, and, in many motors, odd-pole grouping. (Odd-pole grouping will be explained later in this chapter.) If all groups do not contain the same number of coils, it will be odd-pole grouping.

The 12-lead motor can be connected in several ways. Among these are part-winding start, wye-delta, and multiple voltage. Some of the voltages with 12 leads are two delta–220 volts, two wye–380 volts ($\sqrt{3} \times 220$ volts), one delta–440 volts, and one wye–760 volts. Figure 3-116a shows the end of each phase, with the numbers T_{10}, T_{11}, and T_{12} identifying them. Figure 3-116b shows the different voltage connections. This motor is designed for two delta, 220 volts.

Six leads are used on a number of different connections. One of these is a two-wye, part-winding-start motor. Figure 3-117 shows this schematic and the numbers that are used. The leads T_1, T_2, and T_3 go to one of the internal wyes, and Y_7, T_8, and T_9 go to the other wye. These numbers differ from those for another six-lead connection used for a wye start and a delta run. Figure 3-88 is a schematic of this motor, using the numbers T_1, T_2, T_3, T_4, T_5, and T_6, which represent both ends of each phase. Other six-lead connections are used on two-speed motors of various types. These motors use lead numbers T_1, T_2, T_3, T_4, T_5, and T_6. Two-speed motors will be explained later in this chapter.

The concentric windings, although they look different, have the same connections as do the lap windings. One exception is the concentric-wound consequent-pole motor. The consequent-pole motor was explained in "Three-Phase Concentric Windings." Figures 3-118a and b show how the two windings compare.

Both windings have the same number of coil groups, although the span and the number of coils per group are different. The span of a two-pole winding is one-half the circumference of the stator, and the two-pole winding has more coils per group. The span of the consequent-pole winding, four poles in this case, is about one-third the circumference of the stator. There are three coils per group in this 36-slot stator.

PART-WINDING-START MOTORS

NEMA Definition. A part-winding-start induction motor is arranged for starting by first energizing part of its primary winding and then energizing the remainder of this winding in one or more steps. The purpose is to reduce the initial values of the starting current drawn or the starting torque developed by the motor. A standard part-winding-start induction motor is arranged so that one-half of its primary winding can be energized initially and the remaining half can be energized subsequently, both halves then carrying the same current.

As noted above, the main purpose of using part-winding-start motors is to reduce the inrush starting current or to reduce the starting torque developed by the motor. Although part-winding-start induction motors are single-voltage motors, some dual-voltage type polyphase motors (for example, 220/440) are suitable for part-winding starting on 220 volts. The dual-voltage motor is used on the lower voltage by connecting half the winding for start and then connecting both halves in parallel for run. Many of these motors are connected in wye or delta with the nine leads brought out. See Figure 3-119a and b and Figure 3-120a and b.

Refer to Figure 3-119a and note that connecting T_4, T_5, T_6 together doubles the motor's wye points. Connecting T_1, T_2, and T_3 to L_1, L_2, and L_3 energizes one-half of the winding. Connecting T_7, T_8, and T_9 to L_1, L_2, L_3 completes the sequence with both 220-volt wyes in parallel. If the motor has just six leads brought out, leads T_4, T_5, T_6 are connected together permanently inside the motor.

For the delta motor in Figure 3-120a, one-half the motor is connected in delta by connecting T_1 and T_6 to L_1; T_2 and T_4 to L_2; and T_3 and T_5 to L_3. This sequence is completed by connecting T_7 to T_1, T_6 and T_8 to T_2 and T_4, and T_9 to T_3 and T_5, placing both halves in parallel and across the line. If a delta motor has six leads brought out instead of nine, leads T_1 and T_6, T_2 and T_4, and T_3 and T_5 are connected permanently for starting. For running, connect T_7 to T_1 and T_6; T_8 to T_2 and T_4; and T_9 to T_3 and T_5.

For a two-thirds part-winding start, the delta-connected motor has 12 leads brought out, as shown in Figure 3-120b. For starting, the leads are connected as follows: L_1 connects to T_1, T_7; T_{12}; L_2 connects to T_2, T_4, and T_{10}; and L_3 connects to T_5, T_9, and T_{11}. For running, T_6 is added to L_1; T_8 is added to L_2; and T_3 is added to L_3. In practice, all connections are made automatically by means

of a controller designed specifically for this purpose. This is explained in Chapter 4.

Winding the Part-Winding-Start Motor. These motors are wound for a single voltage. The nine- and the 12-lead motors can be used as dual-voltage motors, but only on low voltage as part-winding start, as explained earlier. The six-lead motor is used on the voltage for which it was designed. Figure 3-121 shows a six-lead, two-wye diagram, and Figure 3-122 shows a 12-lead diagram. These are long jumper diagrams. Short jumper–connected motors work just as well but will be noisier on the first step of the starting sequence.

IDENTIFYING THE NINE LEADS OF UNTAGGED THREE-PHASE, DUAL-VOLTAGE, WYE-CONNECTED MOTORS

The following equipment is used for this test:

1. An ac voltmeter. Scale up to 460 volts.
2. A source of three-phase current—208, 220, or 230 volts.
3. A circuit tester, a test lamp or buzzer, and a battery.

The test may be broken down into two main parts:

A. Testing for the four circuits. Continuity test.
B. Connecting the two-lead circuits to their proper phase.

A. Testing for the Four Circuits

STEP 1. Refer to Figure 3-123a. If there is any doubt about the condition of the winding, the circuits should be tested for shorts and grounds, as explained later in "Troubleshooting and Repair." Test the nine leads for complete circuits using the buzzer, lamp, or other circuit tester. If there are four circuits—three of two leads and one of three leads—this motor must be wye connected. Note that the circuits will be T_7, T_8, T_9—the internal wye; T_1–T_4; T_2–T_5; and T_3–T_6. If the test shows three circuits of three leads each, this will be a delta-connected motor. Assuming a wye-connected motor, continue with the next step.

STEP 2. Tag the circuits. Use T_7, T_8, T_9 *permanently* for the three-lead circuit. *Temporarily* tag the three two-lead circuits T_1–T_4, T_2–T_5, and T_3–T_6. We are not certain at this point that the three two-lead circuits are marked correctly, and so our main problem is to locate and mark them correctly.

B. Connecting the Two-Lead Circuits to Their Proper Phase

STEP 1. Assuming a three-phase, 230–460 volt motor in good condition; apply the lower voltage (230) to leads T_7, T_8, and T_9. The motor should run without load. The other leads must remain open.

STEP 2. Measure the voltage across each of the two lead sections. This voltage should be 230 / $\sqrt{3}$, or approximately 130 volts. See Figure 3-123b.

STEP 3. With the motor running, connect temporarily marked T_6 to T_9 and measure the voltage across T_3 and T_7 and across T_3 and T_8 (Figure 3-123c). If these voltages are equal and approximately 340 volts, the connection of T_6 to T_9 will be correct and should be tagged permanently. If equal readings of approximately 130 volts are recorded, reverse T_6 and T_3. If the voltages are unequal, try the connection with another two-lead section until approximately 340 volts is obtained.

STEP 4. Repeat this procedure for each of the other two-lead circuits; for example, connect T_5 to T_8 and test between T_2 and T_7 and between T_2 and T_9. Connect T_4 to T_7 and measure the voltage between T_1 and T_8 and between T_1 and T_9.

STEP 5. In order to check if the connections are correct, connect the motor for low-voltage operation according to the terminal-marking chart. The motor should be able to pull a normal load, and the line amperes should be equal and of normal value. If the motor is concentric wound, it may be necessary to spin the shaft to make it run on part of its windings.

Untagged Dual-Voltage Delta-connected Motor

The following equipment is used for this test:

1. An ac voltmeter. Scale up to 460 volts.
2. A source of three-phase current—230 volts.
3. An ohmmeter.
4. A test lamp or buzzer with battery.

The test consists of the following:

A. Testing for three circuits. Continuity tests.
B. Identifying center tap.
C. Connecting the circuits in the proper places.

A. Testing for Three Circuits

STEP 1. Refer to Figure 3-124a and note that there are three circuits of three wires each. This is true of all nine-lead, dual-voltage, delta-connected motors. Test with buzzer or lamp to identify the three circuits, and mark them A, B, and C.

B. Identifying the Center Tap

STEP 1. Use an ohmmeter for this test and measure the resistance between leads of this three-lead circuit. The two leads showing the highest resistance should be marked temporarily as T_4 and T_9. The other lead is marked T_1 permanently and is the center tap. Refer to Figure 3-124b and note that the resistance between T_4 and T_9 is twice that between T_1 and T_4 or T_1 and T_9.

STEP 2. Repeat this test for the other two circuits, B and C.

C. Connecting the Circuits in the Proper Phases

STEP 1. Connect circuit A to a three-phase, 230-volt line. The motor should run without a load as an open delta motor (see Figure 3-124c).

STEP 2. As we know lead T_1 and we know that the other two leads are T_4 and T_9, we connect what we think is lead T_4 to one of the outer leads of circuit B.

STEP 3. Measure the voltage between T_1 and T_2. This should be approximately 460 volts.

STEP 4. If lead T_5 is connected to T_4, approximately 390 volts will be obtained. This, of course, is wrong. It will be necessary to use the trial-and-error method until the proper voltage is recorded. Stop the motor when making lead changes.

STEP 5. Repeat the above procedure with all the circuits and mark the leads according to terminals shown in Figure 3-124c.

Two-Speed, Three-Phase Motors

It was pointed out previously that the speed of three-phase motors depends on the number of poles and frequency of the current. If the frequency remains the same, then to obtain a different speed from a three-phase motor, the number of poles must be changed. This alteration can be effected by changing the connection between groups. For example, if one phase of a four-pole motor is connected in the usual manner, as shown in Figure 3-125, four poles are produced, causing rotation just under 1,800 rpm. If the same four poles are connected for like

polarity, as in Figure 3-126, four additional poles will be produced, making eight magnetic poles in all and giving a speed just under 900 rpm. The theory of this action was explained in Chapter 1 (page 37 and Figure 1-164). This type of connection is called a *consequent-pole connection*. In all consequent-connected motors producing more than one speed, long jumper connections must be used.

The span of all two-speed, consequent-pole motors is always that of the lower speed. A four- and eight-pole, two-speed motor has 12 groups, the same as a four-pole motor, but the span is about 1–5. The normal four-pole span is about 1–8.

The two-speed, three-phase motor can be connected to have constant horsepower at both speeds, to have constant torque at both speeds, or to have variable torque at both speeds. For constant torque, the motor is usually connected in two parallel, two wye (2Y) for *high* and series-delta (1Δ) for *low* speed. Figure 3-127 shows the connection of the *A* phase for high-speed operation of a four- and eight-pole, three-phase, constant-torque motor. In tracing out the circuit from T_6, note the opposite polarity in adjacent groups of the *A* phase, indicating a four-pole or high-speed connection, and also that the circuit is two parallel. Figure 3-128 illustrates the same motor with the current entering T_1. All groups now have like polarity, thereby forming four consequent poles and making a total of eight poles. This will give the motor *low*-speed operation. T_6 is not used in the series-delta connection.

Constant torque is the most popular connection of the three types. With constant torque, the connection for high speed is two wye. Figure 3-129a is a schematic diagram of the motor connected in two wye. From this diagram, two circuits can be seen going from L_1 to L_2. Each circuit has four groups, two *A* phase groups and two *C* phase groups. When the motor is connected in series-delta, as shown in Figure 3-129b, there is only one circuit containing the four groups of the *A* phase between L_1 and L_2. The two-wye connection allows more current to flow than the one-delta connection does. More current gives the motor more torque. When the speed is increased, more power is needed to keep the torque the same. By connecting the motor in two wye in high speed, the current and magnetic power of the windings are increased in about the same proportion as is the increase in speed. The result of this is the same torque at both high and low speeds. One horsepower is developed when 550 pounds of weight is raised one foot in one second. If the motor has constant torque and can raise 550 pounds in one second on low speed, it will be able to raise the 550 pounds two feet in one second if the speed is doubled, as in high speed. This also means that the motor has one horsepower in low speed and two horsepower in high speed. A constant-torque motor has two different horsepower ratings and two different amp ratings on its nameplate.

Figure 3-130a is the way a four-pole, constant-torque, phase *A* motor is connected, Figure 3-130b is the *B* phase, and Figure 3-130c is the *C* phase. Figure 3-130d shows all three phases put together to form a four- and eight-pole, constant-torque motor.

The entire connection of a four- and eight-pole, constant-torque motor is shown in Figure 3-130e. Six leads are brought out of the motor. For *high*-speed operation, T_6, T_5, and T_4 are connected to the three-phase power supply. T_1, T_2, and T_3 are connected together and taped. For *low*-speed operation, T_1, T_2, and T_3 are connected to the three-phase power supply, and T_6, T_5, and T_4 are taped individually and not used.

For constant horsepower, the connection is the same as for a one-delta, long jumper motor. The one-delta, long jumper connection is illustrated in Figure 3-131a. The only difference is in the jumper that is the center of each phase. This jumper has a lead fastened to it, as can be seen in Figure 3-131b. Figure 3-131c is the *A* phase connected in two wye.

When the constant-horsepower motor is connected in one delta, as in Figure 3-132a, the motor will have four poles and be connected for high speed. When connected in two wye, the groups all will have the same polarity. This will double the poles in the stator, and the motor will have eight poles for low speed. Assuming that this motor can pull 550 pounds one foot in one second in high speed (1,800 rpm), it is rated as one horsepower. The connection for high speed is one delta, and the current going from L_1 to L_2 has one path through four groups. When the motor is connected in two wye for low speed, as in Figure 3-132b, there are two circuits going through four groups from L_1 to L_2. With the circuits doubled, the current and magnetic power increase, and the motor will have more torque. The increase in torque enables the motor to lift 1,100 pounds, but the speed is now one-half (900 rpm), and so the weight will be lifted six inches per second. The motor's power is still rated at one horsepower. The constant-horsepower motor will have a one-horsepower rating and two amp ratings on the nameplate. Figure 3-133a shows the *A* phase; Figure 3-133b shows the *B* phase; Figure 3-133c shows the *C* phase; and Figure 3-133d shows them all put together to illustrate the complete constant-horsepower connection.

Figure 3-133d shows a four- and eight-pole constant-horsepower motor. For *low*-speed operation, T_1, T_2, and T_3 are connected to the power line, and T_4, T_5, and T_6 are connected together and taped. For *high*-speed operation, T_4, T_5, and T_6 are connected to the power supply. T_1, T_2, and T_3 are taped separately and not connected.

The difference between constant horsepower and constant torque is shown in Figures 3-134a and b. The direction in which the jumper is connected from the center of the phase determines whether the groups will be two poles or four poles and as a one-circuit or a series-delta connection. Constant horsepower has two poles when connected in delta, and constant torque has four poles when connected in delta. Constant horsepower resembles a one-delta connection, but constant torque is not similar to any other connection. When comparing the complete diagrams of Figure 3-130d (constant torque) and Figure 3-133d (constant horsepower), each line lead of a constant torque is fastened to one left and one right lead of two coil groups. The constant-horsepower line leads are fastened to either two right leads or two left leads of two coil groups. This is important to know when stripping a stator with no nameplate.

The lead at the center of the phase is the key to connecting all two-speed 1 delta–2 wye motors, no matter how many poles they have. Phase A of the two- and four-pole motor in Figure 3-134a is constant torque, and phase A of the two- and four-pole motor in Figure 3-134b is connected for constant horsepower. The center lead of the phase in a two- and four-pole motor is in the first group.

Phase A of a four- and eight-pole motor shown in Figure 3-135a is constant torque, and phase A in Figure 3-135b is constant horsepower. In these illustrations, the center of the phase is between the second and fourth coil group. Phase A of the six- and 12-pole motor shown in Figure 3-136a is constant torque. Figure 3-136b shows constant horsepower. The center group in this motor is between the fifth and sixth group. The group-to-group long jumpers skip the same number of phase groups in all the motors from four- and eight-poles on, no matter how many poles there are.

Multispeed motors can be operated with two separate windings. When two windings are wound in the same stator, the energized winding will induce or transform a voltage into the idle winding. If the idle winding has a delta connection, the winding will be a closed circuit and a current will flow in it, as shown in Figure 3-137. This current is furnished by the energized winding and will be in addition to its normal full-load current. This additional current will overheat the energized winding and cause it to burn out. To prevent this, the circuit is opened, as shown in Figure 3-138. The lead T_3 normally has two groups fastened to it. The group on the T_5 side of T_3 is brought out with a lead that is called T_7, and the group on the T_4 side of T_3 remains labeled T_3.

The multispeed motor can have two, one-speed windings, two, two-speed windings, or a combination of a one-speed and a two-speed winding. When this is done, any winding with a delta connection must be opened when the other winding is energized. When two windings are used, one winding will be numbered T_1, T_2, T_3, and so on. The second winding will be numbered T_{11}, T_{12}, T_{13}, and so on.

A third type of consequent-pole, two-speed connection is the variable torque. This type is connected in one and two wye. This motor is connected in one wye for low speed and in two wye for high speed. Figure 3-139 shows the A phase as two wye for high speed. Figure 3-140a shows one wye for eight poles and low speed. The end of each phase will terminate at the wye instead of at the start of the next phase, as with the constant-torque motors. Figure 3-140b shows the B phase, and Figure 3-140c shows the C phase. Figure 3-140d is the complete variable-torque, four- and eight-pole diagram.

Consequent-pole, one-speed windings are much easier to install than are normal windings. An eight-pole, consequent-pole, three-phase winding consists of 12 groups, whereas a normal eight-pole, three-phase winding has 24 groups. Figure 3-141 shows an eight-pole, one-speed, consequent-pole, three-phase winding connected in one wye. Figure 3-142 is the same winding connected in one delta. Two windings are sometimes combined for two-winding, two-speed motors. Figure 3-143 shows some multispeed, three-phase connections that were reproduced with permission of the Allen-Bradley Company. When the delta

connection is used in a two-winding motor, there must be an extra lead to allow the delta winding to be opened when the other winding is energized.

There is an exception to this rule. If the two windings are laid in the slots and connected in a certain sequence, the transformed voltage will cancel itself. When taking data on this motor, it is important that the windings and connections be in the same position as the original windings.

ODD-POLE GROUPING

Odd-pole grouping is necessary when the number of slots in a stator does not divide evenly into the number of groups in the winding. A lap-wound stator will usually have the same number of coils as it has slots. Each slot will contain two coil sides. Odd-pole grouping is used because it is more economical to make a winding fit a stator than to build a stator for each type of winding.

The following is the procedure for odd-pole grouping:

1. The number of groups in a winding = poles × phases.
2. The number of coils per group.
3. Distribution of odd groups.

EXAMPLE 1: 48-slot, 6-pole winding.

1. 6 poles × 3 phases = 18 groups.
2. 48 slots/18 groups = 2 12/18 coils per group.

Because there is no such thing as a fraction of a slot, there must be groups that contain two coils and groups that contain three coils. Using the fraction 12/18, the numerator 12 determines the number of groups with the greater number of coils or, in this case, 12 groups of three coils per group. Because there are 18 groups, the remaining six will have two coils per group. The smaller number of groups (six) is considered the odd-pole group.

Distributing the odd-pole groups is the next step. The guidelines for distribution are that Rules 2, 3, and 7 must be followed; the rest are not absolutely necessary but are recommended.

1. The placement of odd groups should be as symmetrical as possible.
2. Each phase *must* have the same number of coils or turns of wire.
3. Each circuit of each phase *must* have the same number of coils or turns of wire.
4. North and south poles should have the same number of coils in each phase.
5. Each half of the stator should have an equal number of odd groups.
6. Dead coils: a. Should not be placed between the same phases.
   b. Should be placed in each half.
   c. Should not be placed across the stator from each other.
7. The number of circuits possible *must* divide evenly into the number of odd-pole groups.
8. The connection may have to be short jumper.

9. The connection sequence may have to start with the first pole group that is placed in the stator.

It has been determined that there are six groups of two coils per group that are considered odd-pole groups: 6 groups/3 phases = 2 odd groups per phase that must be distributed in the two halves of the stator. An easy way to visualize this is shown below. A cluster consists of phases *A*, *B*, and *C* for each pole. Also, polarity is shown as N or S for each group.

First Half 1									*1/2 line*	*Second Half 2*								
1			2			3				1			2			3		
A	B	C	A	B	C	A	B	C		A	B	C	A	B	C	A	B	C
N	S	N	S	N	S	N	S	N		S	N	S	N	S	N	S	N	S
2					2		2			2					2		2	

A good way of distributing the odd poles is to place one odd group of the *A* phase in the first cluster of the first half and the second odd group of the *A* phase in the first cluster of the second half. Next an odd group of the *C* phase is placed in the second cluster of the first half, and the second odd group of *C* phase is placed in the second cluster of the second half. The *B* phase's odd groups are placed in the third cluster of the first and second halves. The last step is to put the majority number, in this case, three, under all the remaining phase letters. Figure 3-144 shows this arrangement.

If all the odd groups are placed in the first cluster of each half, the number of slots occupied by the first cluster will be smaller than the number of slots occupied by the second or third clusters. This will cause a magnetic unbalance that can adversely affect the motor's torque.

There are two odd poles in each phase. Rule 7 states that the number of circuits possible *must* divide evenly into the number of odd-pole groups. This winding can be connected on one circuit, two circuits, or one and two circuits. All grouping arrangements can be connected in one circuit, and all one-circuit connections can be long or short jumper. Two circuits or one and two circuits cannot always be connected long jumper. Rule 4 states that north and south poles should have the same number of coils in each phase. In this case there is one north and one south odd-pole group. The sequence of connecting can start with any group with this arrangement.

EXAMPLE 2: 54 slots, 4 poles.

1. 4 poles × 3 phases = 12 groups.
2. 54 slots/12 groups = 4 6/12.

6 groups of 5 coils per group = 30.

6 groups of 4 coils per group = $\frac{24}{54}$ coils (1 coil per slot).

3. In this case, there are an equal number of groups of four and five. Figure 3-145 shows how this grouping can be arranged. The short jumper–only arrangement is shown first, and the long jumper–only arrangement is next. Either can be connected by starting the sequence at any group. If the long jumper arrangement is connected short jumper, the connecting sequence must start with the first cluster of either half.

Example 3: 80 slots, 4 poles.

1. 4 poles × 3 phases = 12 groups.
2. 80 slots / 12 groups = 6 8/12.

$$\begin{aligned} 8 \text{ groups of } 7 &= 56 \text{ coils.} \\ 4 \text{ groups of } 6 &= \frac{24 \text{ coils}}{80 \text{ coils (or slots).}} \end{aligned}$$

3. Distribution. When the numerator (8) is not divisible by six, there must be dead coils to achieve a balanced winding.

All motors that are not consequent pole will have the same number of north poles as south poles in each phase. For example, a two-pole motor will have a north and a south pole in each phase: 2 poles × 3 phases = 6 groups. A four-pole motor will have two north poles and two south poles in each phase: 4 poles × 3 phases = 12 groups. A six-pole motor will have three north poles and three south poles in each phase: 6 poles × 3 phases = 18 groups. From these examples, we can see that the number of groups are in increments of six. Therefore if the numerator is not divisible by six, there must be dead coils.

A dead coil has the same number of turns as do the other coils in the winding. The dead coil is necessary to maintain the magnetic balance for the winding. The ends of the coil must be insulated so that the coil has no circuit within itself or with any other part of the winding. If the ends were shorted together, there would be a circulating current in the coil that could char the insulation and cause a short. The charring would also short the coils that share the slots with the dead coils.

The location of the dead coil will be shown as the letter *X*. There are charts for odd-pole grouping that signify a dead coil by either printing the group number in **boldface** or underlining the group with a dead coil. But this method does not indicate on which side of the group the dead coil is located. When using these charts, take note of Rule 6.

The 12 groups consist of eight groups of seven and four groups of six. Two of the groups of seven will become groups of six coils per group. This will bring the number of six-coil groups to six and the number of seven-coil groups to six. There will be two dead coils that need to be placed in the winding. Example 2 can be used to place the coil groups, and Rule 6 can be used to locate the two dead coils. Figure 3-146 shows how this can be done.

REWINDING AND RECONNECTING THREE-PHASE MOTORS

Reconnecting for a Change in Voltage

Motors are often brought into shops to be changed to operate on a voltage other than that on the nameplate. For example, it may be a 220-volt, three-phase motor to be changed to operate on 440 volts.

There are several methods, depending on the original connection. If the motor originally had a series connection, it can be converted to a two-parallel connection for half-voltage operation. If the motor was originally a two-parallel–connected motor, it can be changed to operate on twice the voltage by connecting the windings in series.

Thus a six-pole, three-phase, one-wye, 440-volt motor can be converted to operate on 220 volts by reconnecting it as a six-pole, two-parallel wye. If it is a six-pole, three-phase, two-parallel wye type operating on 220 volts, it can be changed to series-wye for 440 volts.

The principle in all reconnections is that the coil voltage remains the same despite the line-voltage change. This was explained when two-voltage motors were discussed. Delta-connected motors can also be reconnected from series to parallel for the lower voltage and from parallel to series for the higher voltage.

Three-phase motors can be reconnected for voltage changes by converting from wye to delta or vice versa. Many variations are possible: for example, from series-delta to two-parallel wye, from parallel-delta to series-wye, and so on.

After some of these changes, the voltage required by the motor may not be a multiple or simple fraction of the original. Thus a wye-connected motor changed to delta should operate on 58 percent of the original voltage. A delta motor changed to a wye connection should operate on 173 percent of the original voltage. In this book no attempt will be made to cover these reconnections in great detail, as many excellent books treat the subject thoroughly.

EXAMPLE: What voltage should be used on a motor if it is changed from two-parallel delta, 220 volts, to series-wye?

Solution: If changed to series-delta, the motor will require 440 volts; a change to series-wye will require $440 \times 1.73 = 760$ volts.

Voltage changes by means of reconnections are not always possible. For example, a four-pole, 220-volt, series-wye cannot be changed for higher-voltage operation, because if a higher voltage is impressed on the series connection, more current will flow through the coils than they were designed for, and they will therefore burn out. Likewise, four-pole, four-parallel wye cannot be reconnected for a lower voltage because there can be no more than four parallels in a four-pole motor.

Rewinding for a Change in Voltage

Three-phase motors can also be rewound for a change in voltage. The only changes necessary are in the number of turns and the size of the wire.

EXAMPLE: If a 220-volt motor is to be rewound to operate on 440 volts, use twice as many turns on each coil and one-half the circular-mil area of wire. In other words, if 40 turns of No. 17 wire were used on the original motor, 80 turns of No. 20 should be used on the new motor.

EXAMPLE: Some motors rated for 230 volts will not handle the load on 208 volts if loaded to the maximum. The turns must be reduced to the ratio of the voltage change. As an example, 230-volt motor has 40 turns: 230/208 = 1.1, 40 turns / 1.1 = 36 turns. If there is enough room, the next size larger wire should be used. An easy way to determine whether there is enough room is to cut the required number of lengths of wire of this size and fit them into the slot.

Rewinding for a Change in Speed

It has been mentioned that the speed of a three-phase motor will decrease if the number of poles is increased, and vice versa. This can be accomplished by rewinding the motor with a redesigned winding. Caution should be used because some rotor designs are not compatible with a change of poles.

If the applied voltage remains the same when changing from a low speed to a higher speed, the number of turns per phase must be decreased. From a high speed to a lower speed, the number of turns per phase is increased.

EXAMPLE: Redesigning a six-pole, 240-volt two-circuit delta to a four-pole, 240-volt motor. Proceed as follows:

1. Change the coil pitch to 1 and $\dfrac{\text{no. of coils}}{\text{no. of poles}} - 1.$

Thus for a 48-slot motor, the pitch is 1 and 48/4 − 1 = 1 and 11.

2. Rewind each coil, using new turns equal to

$$\frac{\text{Orig. speed}}{\text{New speed}} \times \text{orig. turns} = \frac{1200}{1800} = 66\% \text{ of orig. turns.}$$

3. Use a size of wire equal in circular mils to

$$\frac{\text{New speed}}{\text{Orig. speed}} \times \text{c.m. of orig. wire} = \frac{1800}{1200} = 1.5 \times \text{c.m. of orig. wire.}$$

4. Use original method of connection.

Changes for New Frequency

Three-phase motors can be changed to operate on new frequencies by reconnecting or rewinding. Usually rewinding is required. Sometimes it is possible to operate a motor on a different frequency and a different line voltage. For example, a 25- or 30-cycle, 110-volt motor can operate on 60 cycles at 220 volts. This approximately doubles the original speed.

If a change in frequency is desired without an appreciable change in speed, it will be necessary to rewind the motor.

EXAMPLE: Changing a four-pole, 25-cycle motor to operate on 60 cycles at approximately the same speed.

1. 4 pole, 25 cycle = 750 rpm
   8 pole, 60 cycle = 900 rpm
2. Change the pitch of coil for an eight-pole motor.
3. The number of turns in each coil is 750/900 = 83 percent of the number of original turns. Therefore each coil should be wound with approximately 83 percent of the original turns.
4. Use the next larger size of wire.
5. If the motor has 48 slots and 50 turns of No. 18 wire, it should be rewound with 42 turns of No. 17 wire and a pitch of 1 and 6.

Changing from 50 Hz to 60 Hz is done quite often because of the many foreign motors being used. There are two ways to convert these motors; one keeps the same horsepower, and the other keeps the same torque.

For the same horsepower, use the following formula: Old turns $\times \sqrt{(\text{old Hz / new Hz})}$ = new turns. If it is not important to supply the same horsepower, the following formula is used: Old turns × old Hz / new Hz = new turns.

CHANGING CONCENTRIC WINDINGS TO LAP WINDINGS

The first method that we shall explain works best if all the coils in the concentric winding have the same number of turns. This method works with six-group consequent-pole windings and also with 12-group concentric windings that have one coil per slot. The following is a description of this method.

EXAMPLE: A 36-slot, four-pole concentric winding with 40 turns per coil: 40 turns / 1.9 = 21 turns per coil. Most lap-wound, three-phase motors are spanned at 80 percent of full span. The formula for this is (slots/poles) + 1 × 0.8 = 80% span, or (36/4) + 1 × 0.8 = 8, or a span of 1-8. A four-pole lap winding has 12 groups (4 poles × 3 phases = 12 groups). Coils per group =

slots/groups, or 36/12 = 3 coils per group. The data for the new lap winding are 21 turns per coil, span 1-8, 12 groups of three coils. The wire size and connection remain the same. The coils of the lap winding will share the slot with coils of other groups, and so the appropriate insulation procedures described earlier should be used.

Computer software is available for redesigning almost all types of electric motors. Electrical Apparatus Service Association, Inc. (EASA) has developed this software. EASA is a worldwide organization consisting mainly of electric motor service centers and has its headquarters in St. Louis.

When the coils do not have the same number of turns, the best method to convert concentric to lap is to find the number of effective turns of the concentric winding and then to design a lap winding with the same number of effective turns. To find the number of effective turns, the chord factor must be used. Chord factor tables do not always have enough data for all situations. The following explanation will enable the repairperson to understand how these data have been obtained.

Chord Factor

The chord factor is a multiplier (one or less) used to find the number of effective turns in a coil of wire. The components in determining chord factor are (1) the number of teeth in the stator, (2) the number of poles in the stator, and (3) the span or pitch of the coil, which will determine the number of teeth surrounded by the coil.

Each tooth in a stator represents a number of electrical degrees. Figure 3-147 is a portion of a stator that is flattened to illustrate how electrical degrees, the sine wave, and the teeth of a stator are related. One full-pitch coil is shown in each half of the sine wave. This illustration represents a 36-slot stator with a four-pole winding. The formula to determine the number of electrical degrees per tooth is (180° × poles) / the number of teeth in the stator = degrees per tooth. The coil shown in the drawing has the chord factor 1 because it is full span. As explained in Chapter 1, the chord factor is the sine of one-half the angle. The degrees per tooth encompassed by a coil are added to get the angle of the coil. The sine of one-half of this angle is the chord factor. Charts listing all the sine numbers, or a calculator with a sine function, can be used.

A coil with a small span will have a low chord factor and have fewer effective turns than will a coil with a full span. A coil that is over full span, for example, a 1-11 span (four-pole, 36-slot stator) will have the same chord factor as will a coil with a 1-9 span. Concentric windings will often be over full span.

The following shows how to convert to a lap winding a concentric-wound, four-pole, 36-slot motor with a different number of turns in each coil. The original winding data are converted to effective turns.

Span	*Turns*		*Chord factor*		*Effective turns*
1-9	50	×	.984	=	49.2
1-7	32	×	.866	=	27.7
1-5	12	×	.642	=	7.7
					84.6 Total effective turns per group

The next step is to determine the number of coils per group for the lap winding: Slots/groups = coils per group, or 4 poles × 3 phases = 12 groups, or 36 slots/ 12 groups = 3 coils per group.

A 1-8 span will be used as in the previous example, using the formula (slots/poles) + 1 × 0.8 = span. The chord factor for a 1-8 span is 0.939. The effective turns of one group from the old winding are 84.6 turns. The number of effective turns of the old winding/chord factor of new winding = actual turns of new winding: 84.6/0.939 = 90 turns per group in the new winding, or 90 turns/3 coils per group = 30 turns per coil in the new winding, span 1-8. The connection and wire size remain the same.

Ball Bearings

Ball bearings have excellent characteristics for their use in electric motors:

1. A wide selection of seals and protective shields.
2. All angles in smaller motors.
3. Can be permanently greased.
4. Special grease for high temperatures.
5. Allow manufacturers to use smaller air gap.
6. Ease of installation (no reaming).
7. Fewer items required in inventory because of their standard size.
8. Withstand high speeds very well.

The components of a ball bearing are:

1. The outer race.
2. The balls.
3. The spacing strap.
4. The inner race.
5. The shield, seal, or a combination of both.
6. The lubrication.

The outer race provides a track for the balls to carry the load and to retain them as they go over the top. The balls carry the load. The spacing strap keeps the balls spaced evenly. The inner race contains the shaft and moves in an electric motor. The shield keeps the grease in place and will resist some contaminants. The seal

is designed to keep out most contaminants. A bearing can have shields, seals, or a combination of both. Figure 3-148 shows these components. The lubrication is usually grease. Grease is available in low, normal, and high temperature ratings.

Ball bearings have an estimated life based on their running time, load weight, and rpm. Their life can be shortened by many conditions, among which are heat, vibration, impact-type loads, contaminants, misalignment, overloading, carrying electrical current, and too little or too much grease.

Bearings should be changed when they become noisy or loose. The shaft should have no up-down movement and should have very restricted end movement. Some shops change the bearings on all motors that are repaired, with few exceptions.

The ideal way to remove a ball bearing is to pull evenly on only the inner race with a bearing puller or press. But most motors are constructed so that this is not possible, and so the only place to grip the bearing is the outer race. Figure 3-149 shows a wheel puller being used to remove a bearing. A hydraulic press works very well for this, and there are presses built especially for pulling electric motor bearings. Care must be taken to keep the bearings clean. The thrust washers and space washers must be reassembled in the order in which they were originally placed.

The replacement bearing should be selected in accordance with the motor's operating conditions. It may be necessary to choose a sealed bearing because of dust or dirty conditions. If the ambient temperature is high, the choice is a bearing with high-temperature grease. In the case of high temperature, a fit-free bearing can be used. The fit-free bearing is designed with extra tolerance for heat expansion; an electric motor produces uneven heating. The shaft transfers heat to the bearing and the bearing to the end bell. The end bell has more cooling ability and will not expand at the same rate. This puts a lot of pressure on the outer race of the bearing and results in early failure. But the fit-free bearing should handle this expansion problem.

The extra tolerance of the fit-free bearing may allow the shaft to slip in the inner race, or it may allow the outer race to slip in the end bell. In this case, a special liquid plastic is used. The plastic cures to a semihard state and will not allow the components to slip. The semihard plastic will absorb the expansion with little pressure on the bearing, and it is available at electric motor parts dealers.

The shaft and end bell must be inspected for wear caused by the bearing's slipping. If there is wear, the worn area must be rebuilt exactly to the original size, for if there is misalignment, the replacement bearing will overheat.

After removing the old bearing, cleaning and inspecting the parts, and selecting the new bearing, the new bearing can be installed. Several methods are used to do this:

1. Heating the bearing with oil.
2. Heating the bearing dry.

3. Pressing on the bearing with special bearing tubes.
4. Hammering the bearing into place with special bearing tubes and a lead hammer.

Heating the bearing in clean oil will uniformly expand the whole bearing. Once expanded, the bearing is slipped nonstop into place on the shaft. Once the bearing has stopped moving on the shaft, it will shrink to its original size. If it is not in place, it will have to be pressed or hammered into place. Handling the bearing in hot oil can be hazardous, and so use caution.

Dry heating the bearing works much the same as with oil. The bearing is slipped nonstop into place after it is expanded. Figure 3-150 shows one type of bearing heater.

The bearing is pressed onto the shaft by applying pressure on the inner race only. A piece of pipe that has an inside diameter slightly larger than the inside of the bearing's inner race can be used for this. Figure 3-151 shows special tubes made for this purpose. The pressure must be applied uniformly to the bearing's inner race. Also, care must be taken to align the bearing properly with the shaft.

A lead hammer and pipe or tube can be used to drive the bearing into place. The pipe or tube will distribute the blow evenly on the inner race of the bearing. Make sure the bearing is aligned properly with the shaft. The soft lead will reduce the shock of the blow, and the weight of the lead will move the bearing on the shaft. However, a hard blow from a steel hammer can damage a bearing. The outer race should never be used to drive the bearing onto the shaft.

Lubrication is used to reduce the friction between the components of a ball bearing. A sleeve bearing must have a film of oil between the shaft and the bearing, or else the bearing will wear very rapidly. Grease is used in a ball bearing to reduce the heat produced by the friction between the balls and the rest of the components.

In ball-bearing electric motors that are built to allow for greasing, the end bells have two passages. The grease is forced into one passage, pushing the old grease out the other passage. This is done, if possible, while the motor is running. The bearing cavity should be one-third to one-half full when filled properly.

If too much grease is left in the bearing cavity, the bearing will churn the grease and cause it to overheat. Overheating the grease will cause it to separate and break down. When overgreased, the excess grease sometimes is forced into the inside of the motor and will create many problems there.

Reversing Three-Phase Motors

Figure 3-152 shows the three leads of a three-phase motor connected to a three-phase power line for clockwise rotation. To reverse any three-phase motor, it is necessary only to interchange any two of the motor leads, as shown in Figure 3-153. It can also be reversed by interchanging two of the power leads.

TROUBLESHOOTING AND REPAIR

Testing

The three-phase motor should be given tests for the following defects after rewinding: grounds, opens, shorts, and reverses.

Grounds. Use the test leads as shown in Figure 3-154. Connect one test lead to the frame of the motor and one test lead to one of the leads of the motor. If the lamp lights, a winding is grounded. To ensure a thorough test, move the test lead to each lead of the motor.

If the motor is grounded, it will be necessary to locate and remove the ground before making other tests. Just as in other motors, first try to locate the ground by inspection.

Sometimes one lamination is pushed out of place so that its sharp edges cut into the wire. This can usually be remedied by pressing the lamination back into its proper position. Frequently the fault will be found to be the insulation in the slot. Too, the wire may be placed by mistake between the insulation and the slot, or the insulation may have shifted and left the slot core uncovered.

If it is not possible to find the ground by inspection, the ground may be found using the following procedure: If the motor has a wye connection, apply the appropriate current from the test panel (large motors need more current than small motors do), as shown in Figure 3-155. The lead that is closer to the ground will have fewer turns to go through, and so there will be less resistance to the ground, and the current will be higher than from the other leads to the ground. The difference of a fraction of an ampere will point out the phase with the ground. There is very little chance that the ground will be in the exact center of a phase. Bare the wye connection and take a reading from it to the ground, as shown in Figure 3-156. Compare this reading with the reading from the lead to the ground. The higher reading will be the point closer to the ground. Assuming the lead has the higher ampere reading, open the connection between the first and second group from the lead. If the lead still shows a ground (using test light, as in Figure 3-157), the ground is in the first group. If the first group is not grounded, disconnect the splice between the second and third group, and so on, until the grounded group is found. The group must then be removed from the stator and the insulation replaced between the wire and the slot.

The delta-connected motor is tested, as shown in Figure 3-158. The ground will be found between the two leads that have the highest amp reading to the ground. The lead with the highest amp reading will be closer to the ground. Disconnect the splice between the first and second group from this lead and proceed as described above for the wye-connected motor. Check the groups between the lead with the highest amp reading toward the lead with the next highest reading. Figures 3-159 and 3-160 show how to test a one- and two-wye and a one- and two-delta motor for a ground.

The approximate location of the ground can be found by applying for a short time the appropriate current to the grounded phase lead and the frame and then feeling the coils. The groups between the lead and the ground will become warm, and the groups beyond the ground will remain cool. The groups between the lead and the ground will also magnetize the stator up to the grounded group and will attract a screwdriver blade.

Open Circuits. Open circuits in a three-phase motor may be due to a break in the coil or a loose connection at the splices or jumpers. To locate the open, proceed as follows:

Use the test lamp and determine which phase is open. If the motor is series-wye connected, the phase with an open, as shown in Figure 3-161, will not light to the other two phases. Figure 3-161 shows the open to be in the *A* phase. To find the open, remove the insulation covering the jumper splices of the *A* phase and test from T_1 to each splice. The light will light until the open is passed (see Figure 3-162). The open group will be between the splice where there was light and the splice where there was no light. The open may now be located and repaired. If the open is in the coils of the group, it may be necessary to remove the group from the stator to repair it.

When the motor is connected in series-delta, the limited current comparison method may be used. Figures 3-163a, b, and c show where the current would flow and what the amp readings would be if the *A* phase were open. When the current flows through the *B* phase only or the *C* phase only, there are fewer turns of wire in the path than when the current is applied across the open *A* phase. When the path through the *A* phase is open, the current must go through both the *B* and *C* phases. The amps will be much lower across an open phase of a delta-connected motor. The open can now be found by removing the insulation from the jumper splices and applying current from T_1 to each splice. The amp reading should be high until the splice beyond the open is found. Figure 3-163c shows the path that the current takes when these tests are carried out. If a current-limiting test panel is not available, it will be necessary to open the delta connection at one of the leads, as shown in Figure 3-164, and use a test light from splice to splice, as shown in Figure 3-165.

If the motor is connected in two-parallel wye, it will be necessary to determine in which circuit the open is located. This is done by connecting one test lead to the wye connection, as in Figure 3-166, and the other test lead to both sections of each phase in succession. The procedure from here on is the same as in the single-circuit wye.

When the limited current method is used, apply the appropriate current from T_1 to T_2, from T_2 to T_3, and from T_3 to T_1. The phase with an open circuit will have a slightly lower amp reading than will the phases with two circuits. The phase with the open circuit will have the same low amp reading when combined with either phase, as shown in Figure 3-167. An open in a two-circuit delta motor can be found with a test light. Open the lead connections one circuit at a time,

and test from that circuit to one of the other two leads. When the light does not light, the open circuit will be found. Figure 3-168 shows the ampere readings when the limited current method is used. The phase with the open will read fewer amps than the other two will. When the phase with the open circuit is located, the open circuit is found in two-wye or two-delta motors with a clip-on ammeter. Separate the group leads that are fastened to the line leads; apply current to the phase; and check for the current flow in each circuit with the ammeter, as shown in Figure 3-169. The circuit with no amp reading will be open. The group within the open circuit can then be located with the test light, as explained earlier.

Shorts. A short is a path of very low resistance caused by two wires making electrical contact. A shorted winding in a motor is two or more turns of short circuited wire. When several turns are shorted out of the circuit, the resistance of the circuit is lowered; the current will become too high; and the motor will burn out. Shorts can occur when the coil wire is scratched during insertion or from careless handling. One way to find a shorted coil is with an internal growler. Figure 3-170 shows how this instrument is used. The shorted coil or group is located by the vibrations of a hacksaw blade.

It must be remembered that the growler is not effective for parallel-connected motors. All parallels must be disconnected in order to test the winding with the growler. If the growler is held in position for a few minutes, the defective coil or coils will become hot.

Another method of determining a shorted coil or group is to operate the motor for a few minutes. The defective coil will become much hotter than the others and can be located easily by touch.

The "balance test" can be used with a limited current to locate a shorted phase. This test can be used with the stator only or on an assembled motor. If there are no shorts, each phase will have the same, or a balanced, amp reading. A short in a phase will cause the phase to have less resistance and more amperes. Figure 3-171 shows what to expect if the *A* phase of a one-wye motor has a short. There may be less than a one-ampere difference in the unbalance. Figure 3-172 shows a one-delta winding being tested. If a motor has two or more parallel circuits, the shorted circuit may be found using the method described in Figure 3-169. Separate the circuits and check each of them with a clip-on ammeter. The circuit with the high reading will have a short. Dual-voltage motors can be tested as shown in Figures 3-173a and b.

Reverses. Reverses occur when a coil, group, or phase is improperly connected. Reverses in three-phase motors may occur in (1) coils, (2) groups, and (3) phases.

Reversed Coils. In all three-phase motors, the coils of a group are connected so that the current flows through each coil in the same direction. It is possible that the winder may have placed the coils in the slots in the wrong direction.

Visual inspection is the best method of detecting a reversed coil; however, this is not always possible. An accurate check is to pass a low-voltage direct current from a battery through each phase and place a compass against the core. The compass needle should reverse at each group of one phase, and indicate N at one group, S at the next group, and so on. If at any group the compass needle is indefinite, there may be a reversed coil in that group. The reversed coil builds up a magnetic field that opposes that set up by the other coils, and this causes a very weak field, which has little effect on the compass needle.

Reversed Coil Groups. To test for reversed groups, connect one lead of a low-voltage, dc line to the wye point and the other lead to each phase in order. Move a compass inside the stator to indicate the polarity of each group. If the compass needle reverses at each group as shown in Figure 3-174, the correct polarity is indicated. To test a delta-connected motor for reversed groups, open one delta point and connect a source of low-voltage direct current to the two wires. If the compass needle reverses at each group, the polarity is correct. If a group is reversed, there will be a magnetic opposing action in the circuit. This opposing action will cause a high current flow in the affected circuit. This high current reading may be confused with a short when using the balance test. An excellent instrument for detecting reversed coils or groups is a modified squirrel-cage rotor. The rotor must be fitted to a long shaft and modified so that it will spin freely. Figure 3-175 shows how to use this instrument. Apply a controlled three-phase current to the windings and slowly move the rotor around the inside of the stator. The rotating magnetic field will cause the rotor to spin. When the reversed coil is found, the rotor will stop or will reverse itself. If a method to limit the three-phase current is not available, a motor connected for 460 volts can have 230 volts applied for a short time for this test.

Reversed Phases. A common error in connecting a three-phase motor is to connect the middle phase in the wrong manner. This mistake is easily found with the compass. Connect the phases to the low-voltage direct current as in testing groups—and test with the compass from group to group for reversal of the needle. If the needle indicates three north poles and three south poles, as shown in Figure 3-176, it is an indication of an improperly connected middle phase. Reverse the *B*, or middle, phase to obtain the correct connection. When the test rotor is used in a stator with a reversed *B* phase, it will not spin in any position.

After the motor is tested, it may be dipped and baked. Some procedures require the motor to be preheated before dipping it in varnish. Be sure to follow the directions given for the particular varnish being used.

Common Troubles and Repairs

The symptoms encountered in defective three-phase motors are given below. Under each symptom are listed the possible troubles. The number in parentheses

after each trouble indicates the correspondingly numbered remedy to be found in the following pages.

1. If a three-phase motor fails to start, the trouble may be
   a. Burned-out fuse (1).
   b. Worn bearings (2).
   c. Overload (3).
   d. Open phase (4).
   e. Shorted coil or group (5).
   f. Open rotor bars (6).
   g. Wrong internal connections (8).
   h. Frozen bearing (9).
   i. Defective controller (10).
   j. Grounded winding (11).
2. If a three-phase motor does not run properly, the trouble may be
   a. Burned-out fuse (1).
   b. Worn bearings (2).
   c. Shorted coil (5).
   d. Reversed phase (12).
   e. Open phase (4).
   f. Open parallel connection (13).
   g. Grounded winding (11).
   h. Open rotor bars (6).
   i. Incorrect voltage (7).
3. If the motor runs slowly, the trouble may be
   a. Shorted coil or group (5).
   b. Reversed coils or groups (8).
   c. Worn bearings (2).
   d. Overload (3).
   e. Wrong connection (reversed phase) (12).
   f. Loose rotor bars (6).
4. If the motor becomes excessively hot, the trouble may be
   a. Overload (3).
   b. Worn bearings (2) or tight bearing (9).
   c. Shorted coil or group (5).
   d. Motor running on single phase (4).
   e. Loose rotor bars (6).

1. Burned-out Fuse. Remove fuses and test with test lamp as shown in Figure 3-177. If the lamp lights, the fuse is good. A burned-out fuse is indicated when the test lamp does not light.

To test fuses without removing them from the holder, a voltmeter must be used. If a test light designed for 230 volts is mistakenly used on 460 volts, it will blow out and may trigger a severe electrical explosion. If the fuse is open, there will be a line voltage read across it, as shown in Figure 3-178.

If the fuse burns out while a three-phase motor is in operation, the motor will continue to operate as a single-phase motor (Figures 3-179 and 3-180). This

means that only part of the winding is carrying the entire load. If the motor continues to operate in this manner, even for a short time, the winding will become very hot and burn out. Further, the motor will be noisy in operation and may not pull the load. To find the trouble, stop the motor and try to start it again. A three-phase motor will not start with a burned-out fuse. To remedy this condition, locate and replace the defective fuse.

If the motor is a parallel-connected wye, current will be induced in the open phase and cause the winding to burn out quickly. This should be prevented if possible.

*2. **Worn Bearings.*** If a bearing is worn, the rotor will ride on the stator and cause noisy operation. When the bearings are so worn that the rotor rests firmly on the core of the stator, rotation is impossible. To check a small motor for this condition, try moving the shaft up and down, as shown in Figure 3-181. Motion in this manner indicates a worn bearing. Remove and inspect the rotor for smooth, worn spots. These indicate that the rotor has been rubbing on the stator. The only remedy is to replace the bearings.

On a large open motor, the check for worn bearings is made with a feeler gauge, shown in Figure 3-182. The air space between the rotor and the stator must be the same at all points (Figure 3-183). If it is not, the bearing must be replaced.

*3. **Overload.*** To determine whether a three-phase motor is overloaded, remove the belt or load from the motor and turn the shaft of the load by hand (Figure 3-184). Usually a broken part or dirty mechanism will prevent the shaft from moving freely.

Another method is to use an ammeter on each line wire. A higher current reading than on the nameplate may indicate an overload. Many shops and motor repairpersons use a snap-around volt ammeter and ohmmeter to test the current in the main line leads feeding the motor. The current in each lead should be the same and approximately the same as the nameplate reading. An excessive reading in one phase indicates a shorted phase. This instrument can be used on all motors from split-phase through three-phase and can be used to test voltage, resistance, and current. It can be used to test unmarked leads on split-phase motors by using the ohmmeter and also to test voltage across components in motors and starters. Figure 3-185 illustrates a method of testing line current in a three-phase motor.

*4. **Open Phase.*** If an open occurs while the motor is running, it will continue to run but will have less power. An open circuit may occur in a coil or group connection.

The motor will continue to run if a phase opens while the motor is in operation but will not start if at a standstill. The conditions are similar to those of a blown fuse.

5. Shorted Coil or Group. Shorted coils will cause noisy operation and also smoke. After locating such defective coils by means of the eye or balance test, the motor should then be rewound.

When the insulation on the wire fails, the individual turns become shorted and cause the coil to become extremely hot and burn out. Other coils may then burn out, with the result that an entire group or phase will become defective.

6. Open Rotor Bars. Open rotor bars will cause a motor to lose power. One sign of open bars is when a motor is connected to the right voltage at no load, it has a very low amp reading. A light load will pull down the speed, and at full load the motor will run below the nameplate speed. This high amount of slip will cause the motor to overheat because of the high current. Open or cracked rotor bars are hard to locate visually in a cast-aluminum rotor. Two methods of locating these opens are explained in Chapter 1 on page 68.

Some special-duty motors or large motors have brass or copper bars. It is possible for these bars to be open or loose in the end rings. Loose bars are repaired by soldering or welding them to the end rings. There must be a good electrical connection between the bars and the end rings. Broken bars must be replaced. The bars usually break because of a loose fit in the rotor slots. The bars will move and vibrate when the motor starts and runs, causing them to crack and break.

7. Incorrect Voltage. Some T-frame motors are designed for a definite voltage. Thus a motor designed for 208 volts will overheat when operated on 250 volts, and a motor designed for 250 volts will not have enough power if operated on 208 volts. If the motor is rated 208-220-440 volts on the nameplate, it will operate well on a range of voltages. Voltage problems become more serious when the motors are loaded to their rated horsepower. If there are problems with a motor designed for the wrong voltage, it should be replaced with one of the right voltage. If it is burned out, the turns may be changed using the formula found in Chapter 1, "Rewinding for a Change in Voltage."

8. Wrong Internal Connections. A good method of determining whether or not a polyphase motor is connected properly is to remove the rotor and place a large ball bearing in the stator. The switch is then closed to supply current to the winding. If the internal connections are correct, the ball bearing will rotate around the core of the stator, as shown in Figure 3-186. If the connections are incorrect, the ball bearing will remain stationary.

For medium- and large-sized motors, reduced voltage should be used; otherwise, a fuse may blow.

9. Frozen Bearing. If oil is not supplied to the part of the shaft that rotates in the bearing, the shaft will become so hot that it will expand sufficiently to prevent movement in the bearing. This is called a *frozen* bearing. In the process

of expansion, the bearing may weld itself to the shaft and make rotation impossible.

To repair, try to remove the end plates. The end plate that cannot be removed easily contains the bad bearings. Remove the end plate and armature as a unit; hold the armature in a stationary position, and turn the end plate back and forth. If it is impossible to move the end plate, loosen the setscrew that holds the bearing in the housing, and try to remove the armature and bearing as a unit. Be careful to keep the oil ring free from the bearing while this is being done. The bearing can then be removed by tapping it with a hammer. The shaft will probably have to be turned down on a lathe to a new size and a new bearing made. If ball bearings are used, replace with new ones.

10. Defective Controller. If the contacts on the controller do not make good contact, the motor will fail to start. To locate trouble and repair this unit, see Chapter 4.

11. Grounded Winding. This will produce a shock when the motor is touched. If the winding is grounded in more than one place, a short circuit will occur which will burn out the winding and perhaps blow a fuse. Test for a grounded winding with test lamp and repair by rewinding or by replacing the defective coil.

12. Reversed Phase. This will cause a motor to run more slowly than the rated speed and produce an electrical hum indicative of wrong connections. Check the connections and reconnect them according to plan.

13. Open Parallel Connection. This fault will produce a noisy hum and will prevent the motor from pulling full load. Check for complete parallel circuits.

Chapter 4

ALTERNATING-CURRENT MOTOR CONTROL

If an ac motor is started on full voltage, it will draw from two to six times its normal running current. Because the motor is constructed to withstand the shock of starting, no harm will be caused by this excessive flow of current. However, on very large motors, it is generally desirable to take some measure to reduce the starting current; otherwise, damage may be done to the machinery driven by the motor, and line disturbances may be created that affect the operation of other motors on the same line.

For the small motor or when the load can stand the shock of starting and no objectionable line disturbances are created, a hand-operated or an automatic starting switch can be used for control of the motor. This type of switch connects the motor directly across the line and is called an *across-the-line-starter*, or a *full-voltage starter*.

In the case of the large motor, when the starting torque must develop gradually or when the high initial current will affect the line voltage, it is necessary to insert in the line some device that will reduce the starting current. This device may be a resistance unit or an autotransformer. Controllers that use this method of starting a motor are called *reduced-voltage starters*. Controllers are also used to protect the motor from overheating and overloading, to provide speed control, to provide for reversing the motor, and to provide undervoltage protection.

The following popular types of controllers will be described: pushbutton switch starters for small motors, magnetic across-the-line starters, reduced-voltage resistance starters, solid-state reduced-voltage starters, compensator starters, wye-delta starters, drum starters, part-winding starters, two-speed controllers, adjustable-frequency speed controllers, and plugging and braking controllers.

WIRING DIAGRAMS AND LINE DIAGRAMS

There are two kinds of diagrams of a control, wiring diagrams and line diagrams. The wiring diagram shows all the devices in the system in the position in which they are located in the enclosures. The wiring diagram is helpful when the de-

vices are being installed. They show exactly where the power lines, control devices, and the motor are connected. But the wiring diagram is hard to trace when it is necessary to understand the electrical sequence of circuits. Figure 4-1 is a wiring diagram.

The line diagram, also called a ladder diagram, elementary diagram, or schematic diagram, is drawn out to show the devices in as straight a line as possible from line 1 to line 2 (Figure 4-2). The heavier power circuits are sometimes left out for clarity.

A wiring diagram is made to show how to connect control devices and to aid in physically tracing out the circuits when troubleshooting.

A line diagram is the simplest way to present circuits so that their function can be understood. Figure 4-2 points out an important fact to remember; all control circuitry is connected between L_1 and L_2 in three-phase controllers. Breaking down the control circuitry farther, between L_1 and the holding coil of the control (M) is where all the ON-OFF switching is located. And between the control holding coil (M) and L_2 is where all the overload contacts are connected. This is typical of all controllers.

STARTERS

Pushbutton Switch Starter for Fractional-Horsepower Motors

The pushbutton switch starter for fractional-horsepower motors is a simple type of switch that connects the motor directly to the line. Two pushbuttons are located on the switch, one for starting and the other for stopping the motor. Pressing the START button causes the contacts inside the switch to make and connect the motor across the line. Pressing the STOP button causes the contacts to break apart and open the circuit to the motor. This type is shown in Figure 4-3.

The usual type of pushbutton switch starter is equipped with a thermal overload device connected in series with the line. It opens the circuit to the motor if an overload current persists for a short period of time. Figure 4-4 shows one type of overload device that consists of a small cylinder containing an alloy that will melt when an overload persists. Embedded in the metal is a small shaft to which is attached a ratchet wheel. When the START button is pressed, the shaft is held in place by a spring that engages the ratchet wheel. If an excessive current passes through the overload device, the alloy in the cylinder will melt and cause the START button to spring to its OFF position and disconnect the motor from the line. To restart the motor, it is necessary to wait several seconds until the metal hardens.

Another switch used on fractional-horsepower motors is of the ordinary snap-action type. This switch contains a thermal relay to provide overload protection. A coil of resistance wire is connected in series with one motor lead so that it heats

when excessive current flows. A solder film that will melt from heat is located inside the coil. When the solder film melts, a trigger is tripped, releasing the main contacts of the switch.

Most of these starters can be used for single- or three-phase motors. Figure 4-3 shows a diagram of a pushbutton starter connected to a single-phase motor, and Figure 4-5 shows such a starter connected to a three-phase motor. In Figure 4-3, when the START button is pressed, it closes the contacts L_1 and L_2 and connects the motor across the line. If an overload occurs, the thermal relay will trip the releasing mechanism and cause the contacts to open, thereby stopping the motor. To reset the tripping mechanism, it is usually necessary to press the STOP button. If the motor is running normally and it is necessary to stop it, the contacts are released by pressing the STOP button. Figure 4-6 shows different types of manual starters.

Magnetic Full-Voltage Starter

A starter that connects a motor directly across the line is called a *full-voltage* starter. If this starter is operated magnetically, it is called a *magnetic* full-voltage starter. A magnetic starter designed to operate a three-phase motor is shown in Figures 4-7 and 4-8. Some of the wiring symbols in this and other diagrams are shown in Figure 4-9. Figure 4-8 has three normally open main contacts that, when closed, connect the motor directly to the line. It also has a magnetic holding coil, which closes the main contacts upon being energized and also closes a normally open auxiliary or maintaining contact to maintain the current in the holding coil. The main and auxiliary contacts are generally joined by an insulating connecting bar so that all contacts will close when the holding coil becomes energized. It is obvious that any size of magnetic switch can be operated just by sending a small current through the coil. Starters are often equipped with dual-voltage coils for operation on either high or low voltage. Coils are made in two sections—series for high voltage, parallel for low voltage.

Two overload relays are shown in Figure 4-7. All three-phase starters are now made with provisions for a third overload relay as standard equipment, as shown in Figure 4-8.

The holding coil on an ac magnetic starter is excited by a pulsating current, and therefore its pull is not continuous but, rather, alternates according to the frequency of the current. This tends to cause chattering; to overcome this condition, the core of the magnet is equipped with a shading coil that produces an out-of-phase flux. The shading coil is a small, single-turn copper coil embedded around a portion of the core tip. The current induced in this coil is sufficient for the magnet to retain the contactor during the reversal of current. A complete magnetic starter is pictured in Figure 4-10.

An advantage of a magnetic starter over a manual starter is that is may be operated merely by pressing a pushbutton which may be located some distance

from both the starter and the motor. This lends to convenience and safety in starting and stopping a motor, especially if it is of high voltage or if is must be controlled from one or more remote points.

Overload Relays. Nearly all magnetic starters are equipped with an overload device to protect the motor from excessive current. Two types of overload relays are used on magnetic starters, and these are either magnetic or thermal in operation. The thermal overload relay may be either the bimetallic or solder-pot type.

A thermal relay is illustrated in Figure 4-11a and b. This bimetallic type of relay consists of a small heater coil or strip that is connected in series with the line and that generates heat by virtue of the current flowing through it; the amount of heat generated depends on the current flow in the line. Mounted adjacent to, or directly inside, the coil is a strip formed of two metals. This is fixed at one end, the other end being free to move. The two metals have different degrees of expansion, and the strip will bend when heated. The free end normally keeps two contacts of the control circuit closed. When an overload occurs, the heater heats the thermostatic bimetal so that it will bend and separate the two contacts, thereby opening the holding-coil circuit and stopping the motor. The bimetallic type of overload relay is usually designed with a feature that permits automatic resetting, although it is also designed for manual resetting. Some overload relays are ambient compensated to provide maximum protection when the temperature surrounding the relay differs from the temperature surrounding the motor. A number of manufacturers feature a bimetallic overload relay that can be converted from manual to automatic by positioning a reset selector lever. Automatic reset is desirable when control is not readily accessible or regularly attended. Some overload relays are trip free. This means that the starter contacts cannot be held closed during an overload and cause damage to the motor.

The solder-pot type of thermal overload relay consists of a eutectic alloy element, heater coil, normally closed contacts, and a reset button (Figure 4-12). The eutectic alloy element contains a solder that a specific temperature immediately changes from a solid state to a liquid state. The heater coil carries the main line current and surrounds the thermal element. When an excessive current flows through the heater coil, the heat generated by the coil melts the eutectic alloy in the thermal element, allowing a shaft and ratchet wheel assembly within the sleeve to turn and trip the normally closed contacts. This opens the holding-coil circuit, causing the main contacts to open and disconnect the motor from the line. To restart the motor, the reset button is pressed after the solder has cooled. This type of relay is manually reset and is trip free. This prevents holding the contacts closed by pressing the reset button. This important protective feature prevents forcing the motor to operate under persistent overload conditions. Use of this type of overload relay is desirable because the necessity of resetting the relay draws attention to the cause of the overload and because the possibility of injury to persons by the automatic restarting of a motor is eliminated.

Number of Overload Relays Required

The National Electrical Code clearly indicates the minimum number of overload units to be used for the protection of single phase, three-phase, and dc motors.

The code, generally, requires one overload unit for single-phase and dc motors and three overload units for all three-phase motors. Figures 4-13a, b, and c show three controllers manufactured by three different companies. Note the overload units.

Pushbutton Stations

Magnetic starters are controlled by means of pushbutton stations. The most common station has START and STOP buttons, as shown in Figure 4-14. When the START button is pressed, two normally open contacts are closed; and when the STOP button is pressed, two normally closed contacts are opened. Spring action returns the buttons to their original position when finger pressure is removed. To operate a magnetic switch by a START-STOP station, it is necessary to connect the holding coil to the station contacts so that when the START button is pressed, the coil will become energized; and when the STOP button is pressed, the holding-coil circuit is opened.

A diagram of a typical full-voltage magnetic starter equipped with three thermal overload relays and connected to a START-STOP station is shown in Figure 4-15. In the diagrams to follow, the motor circuits are indicated by heavy lines, and the control circuits are shown by light lines. The operation of this starter is as follows:

When the START button of Figure 4-15 is pressed, it completes the circuit from L_1 to the normally closed contacts of the STOP button through the holding coil M and normally closed contacts of the overload relays to L_2. Thus, the coil is energized, and it closes contacts M and connects the motor across the line. A maintaining circuit is completed at point 2 to keep the holding coil energized after the finger is removed from the START button. Pressing the STOP button opens the coil circuit and causes all contacts to open. If a prolonged overload should occur during the operation of the motor, the overload relay contacts will open and deenergize the holding coil. If an overload condition has caused the relay to trip, it will be necessary to reset the relay contact by hand before the motor can be restarted.

Figure 4-16 shows a line diagram of the control circuit. Figure 4-17 is a line diagram of the starter. Coil M is used to close main contacts M; OL is the normally closed overload relay contact.

Magnetic full-voltage starters are made by *all* controller manufacturers. A typical controller is shown in Figure 4-18. Figures 4-19 and 4-20 show controllers with a step-down transformer in the control circuit. This permits operating the control circuit at a lower voltage than the line voltage and is usually done for safety reasons.

If a control-circuit transformer is used, the primary should be connected to the line terminals of the starter. A separate voltage source is hazardous to personnel and machine unless it is disconnected when the contactor coil is opened.

Note that in these diagrams one end of the secondary is grounded and one side of control coil M is connected to the grounded side. It is important when one side of the control circuit is grounded that the control circuit be so arranged that an accidental ground in the remote control devices will not start the motor. Overload contacts are always connected between coil M and L_2.

Combination Starters. A combination starter consists of a magnetic starter and disconnect switch mounted in the same enclosure. These starters are supplied with either a fused disconnect switch or a circuit breaker. The fuses (or circuit breaker) provide short-circuit protection by disconnecting the line. A combination starter and circuit breaker will prevent single phasing by simultaneously opening all lines when a fault occurs in any one phase. This type of starter can be quickly reset after the fault has been cleared. Figure 4-21 illustrates a fused combination starter. Figure 4-22 shows a combination starter and circuit breaker.

Pushbutton-Station Connections. A number of control circuits will be illustrated using various combinations of pushbutton stations. All of these diagrams employ one type of magnetic switch, but others can be used. Figure 4-23 illustrates a magnetic switch that is operated from any of three stations. Figure 4-24 shows a straight-line diagram of the control circuit of three START-STOP stations. Figure 4-25 gives the control circuit of two START-STOP stations. In these diagrams, the START buttons are connected in parallel, and the STOP buttons are connected in series. This must be done regardless of the number of stations. Note that the maintaining contact is always connected across the START button. All STOP buttons are connected in series with one another and in series with the holding coil, so that the motor can be stopped from any position in case of emergency.

Jogging. Magnetic switches can be "jogged" or "inched." By this method the motor is made to run only while the finger is pressing the JOG button. As soon as pressure is removed, the motor stops.

Jogging may be accomplished by using (1) a station with a selector pushbutton, (2) a station with a selector switch, or (3) a station with standard pushbuttons and a jog relay.

Figure 4-26 shows a full-voltage magnetic starter connected to a START-JOG-STOP station having a selector pushbutton. This button is constructed with a sleeve that may be turned to either a JOG or a RUN position. With the sleeve turned to the RUN position, the START and STOP buttons function as in an ordinary START-STOP station. With the sleeve in the JOG position, the circuit to the holding contacts is broken, and the motor will run only when the JOG button is held down. Depressing the START button cannot cause the motor to run.

The operation of the control circuit of Figures 4-26 and 4-27 is as follows: With the selector sleeve on RUN, pressing the START button completes a circuit from L_1 through the STOP button and the closed contacts of the JOG selector button, the start contacts, the holding coil, the overload contacts, and to L_2. This energizes the holding coil, causing contacts *M* to make and connect the motor across the line. The maintaining contact keeps the holding coil in the circuit after the finger is removed from the START button. Pressing the STOP button opens the coil circuit and stops the motor. With the selector sleeve on JOG, current cannot flow to the START button because the front contacts are in the OPEN position. Depressing the JOG selector button completes a circuit through the STOP button, the back contacts of the selector button, the holding coil, the overload contacts, and to L_2. The motor will run only when the button is depressed.

Figures 4-28, 4-29, and 4-30 show jog stations that use a selector switch rather than a selector button. The START button is used to jog or to run the motor, depending on the position of the switch. In each case, with the button in the JOG position, the circuit to the holding contact is broken. A station in which the START button is used for starting and jogging is shown in Figure 4-31. A magnetic switch operated by this type of station is illustrated in Figure 4-32. Another method of jogging is through the use of a jogging relay, as shown in Figures 4-33 and 4-34.

When the START button is pressed, the relay coil is energized, thus closing the relay contacts, *CR; CR* closes the circuit for the holding coil, causing contacts *M* to close. This completes the maintaining circuit for the holding coil, *M,* when the start button is released. In the meantime all the main contacts are made, closing the circuit to the motor. If the JOG button is pressed while the motor is at standstill, a circuit is formed through the holding coil only as long as the button is pressed. It is impossible for the starter to lock in, no matter how quickly the finger is withdrawn.

Another diagram showing the connections of a jog relay and magnetic switch is given in Figure 4-35. Pushing the START button operates the motor starter and jog relay, causing the starter to lock in through one of the relay contacts. When the JOG button is pressed, the starter operates, but this time the relay is not energized, and thus the starter cannot lock in.

A control circuit is shown in Figure 4-36. In this diagram, when the JOG button is depressed, the jog relay is bypassed, and the main contactor coil is energized solely through the JOG button. When the button is released, the contactor coil releases immediately. Pushing the START button closes the control relay, and it is held in by its own normally open contacts. The main contactor coil in turn is closed by another set of normally open contacts on the jog relay and is held in.

***START-STOP* Station with a Pilot Light.** Sometimes it is advisable to have a pilot light on the pushbutton station to indicate whether the motor is running. The lamp usually is mounted on the station and is connected across the holding coil. Such a connection is shown in Figures 4-37 and 4-38. Figure 4-39 shows a

control circuit with pilot light ON when motor is *stopped*. Normally closed contacts are needed on this starter. With the motor running, these contacts are open. Contacts are closed when the motor is stopped and the pilot light goes on. A START-STOP station with a pilot light is pictured in Figure 4-40.

Full-Voltage Reversing Starter. The magnetic starters shown thus far are designed to operate the motor in one direction, either clockwise or counterclockwise. If it is necessary to reverse the motor, its connections must be changed.

Some applications, such as conveyors, hoists, machine tools, elevators, and others, require a motor starter that can reverse the motor when a button is pressed. Thus, two of the line leads can be interchanged to reverse a three-phase motor by means of a magnetic reversing switch. A reversing starter of this type is shown in Figure 4-41. The circuit is given in Figures 4-42 and 4-43. Note that it is necessary to use a FORWARD-REVERSE-STOP station with three buttons and that two operating coils are used, one for forward rotation and the other for reverse rotation.

Two sets of main and auxiliary contacts are used. One set closes when forward operation is desired; the other set closes for reverse rotation. These contacts are connected in such a manner that two line wires feeding the motor are interchanged when the reverse contacts close.

In operation, pressing the FORWARD button completes a circuit from L_1, the STOP button, the FORWARD button, the forward coil, and the overload contacts to L_2. This energizes the coil, which closes the contacts for forward operation of the motor. Auxiliary contacts F also close, maintaining the current through coil F when the button is released. Pressing the STOP button opens the circuit through the forward coil which releases all contacts. Pressure on the REVERSE button energizes the reverse coil which closes the reverse contacts. Terminals T_1 and T_3 are now interchanged, and the motor reverses.

Usually, reversing starters are equipped with a mechanical interlock in the form of a bar which will prevent the reverse contacts from making while the forward contacts are closed. This bar is pivoted in the center, and when the forward contactor goes in, it moves the bar into a position where it is impossible for the reverse contacts to make. This starter does not have an electrical interlock to prevent the forward and reverse coils from being energized simultaneously.

All of these starters are equipped with overload relays, generally of the thermal-relay type.

Sometimes more than one FORWARD-REVERSE-STOP station is used to control a magnetic reversing switch. Figure 4-44 shows connection diagrams of two such stations in different positions.

Besides having a mechanical interlock, most reversing starters are also electrically interlocked. In this system, additional normally closed auxiliary contacts are used to prevent the forward and reverse contactors from being energized at the same time. The holding circuit of each main contactor coil is wired through

the normally closed auxiliary contacts of the opposing contactor, thus providing the electrical interlock.

Figure 4-45 shows a magnetic reversing starter with mechanical and electrical interlocks and a FORWARD-REVERSE-STOP pushbutton station. The STOP button must be depressed before changing directions. Limit switches can be added to stop the motor at a certain point in either direction. Connections *A* and *B* must be removed when limit switches are used. A line diagram of the control circuit is shown in Figure 4-46.

In operation, pressing the FORWARD button closes a circuit from L_1 through the STOP button, the FORWARD button, the reverse normally closed auxiliary contacts, the forward limit switch (if used), the forward coil, and the overload contacts to L_2. The maintaining contacts for the forward coil keep it energized when pressure is removed from the button. At the same time, the normally closed forward auxiliary contacts are opened, preventing a complete circuit through the reverse coil.

A momentary contact pushbutton station that permits immediate reversal of direction without first pushing the STOP button is shown connected to a full-voltage magnetic reversing starter in Figure 4-47. Note that this is also electrically interlocked. Note also that the FORWARD and REVERSE buttons each have a normally closed and normally open contact. Figure 4-48 shows a line diagram of the control circuit.

In operation, pressing the FORWARD button completes a circuit from L_1 through the STOP button, the normally closed contacts of the REVERSE button, the forward contacts, the limit switch (if used), the normally closed reverse auxiliary contacts of the electrical interlock, the forward coil, the overload contacts, and to L_2. The forward coil becomes energized, all the contactors close, and the motor runs. At the same time the normally closed forward contacts are broken, preventing a circuit to the reverse coil. When the forward contactor coil is energized, the forward maintaining contacts are closed, keeping the coil energized, and the forward normally closed auxiliary contacts in series with the reverse coil are opened, preventing the reverse coil from becoming energized. To reverse the motor, press the REVERSE button. This opens the circuit to the forward coil and closes the circuit to the reverse coil.

It is sometimes necessary to operate a reversing magnetic controller from two places. Figure 4-49 shows how two stations can be connected for that purpose. Figure 4-50 is an elementary diagram of a reversing magnetic controller with an electrical interlock controlled by a FORWARD-REVERSE-STOP station wired for changing direction without pushing the STOP button. Figure 4-51 shows a control circuit using a step-down transformer for reduced coil voltage.

Reversing magnetic starters are made in numerous designs. Figure 4-52 shows a starter similar to that of Figure 4-42, except that it is of the vertical type instead of the horizontal type. The starters are mechanically and electrically identical, the only difference being in the panel layout. The operation of this starter is exactly the same as that of the starter described in Figure 4-42.

Reduced-Voltage Starters

If a squirrel-cage motor is connected directly across the line, the starting current will be several times the normal running current. In very large motors this abnormal flow may be injurious to the driven machinery.

On small motors this injurious effect is seldom noticeable, so that across-the-line starters may be used safely. For the large motor, however, it is sometimes necessary to use a starter that will hold the starting current at a safe value. The need for these starters depends a great deal on the construction of the motor and the use to which it is put.

The following controllers will be treated in this section: primary-resistance starters; secondary-resistance starters; and autotransformer starters—compensators, wye-delta starters, part-winding starters, and solid-state, reduced-voltage starters.

Primary-Resistance Starters. When resistance is placed in series with the windings of a three-phase motor, the motor will have less power than if it is connected across the line. The amount of current that flows in the motor's circuits is reduced to whatever value the resistors will allow. The speed is determined by the load applied to the shaft. If there is no load, the motor will accelerate to near-synchronous speed. The motor will accelerate more slowly than if line voltage is applied and will draw less current. With this type of starter, the motor is started with resistors in series with the windings. After the motor accelerates to a certain speed, the contacts in parallel with each resistor close. The current then bypasses the resistor, and more current flows in the motor. When all the resistors are bypassed, the motor will pull its rated load at its rated speed.

Resistance starters may be used in either the stator (primary) circuit or the rotor (secondary) circuit. In the latter case, a wound rotor with three slip rings is used. The motor will be discussed later in this book.

RHEOSTAT TYPE OF RESISTANCE STARTER. There are two types of primary-resistance starters: manual resistance starters of the rheostat type and automatic resistance starters. The rheostat type of starter (old) for a three-phase motor is shown in Figure 4-53. It can also be used for a repulsion-induction motor. The resistances are connected in two of the three phase lines. The arm of this rheostat consists of two sections insulated from each other. Under each section, a metal strip, usually made of copper, rides on contacts that are connected to taps on the resistances.

As the arm is moved, sections of resistance are cut out, increasing the speed of the motor. The starter is so constructed that equal amounts of resistance are removed from each line as the arm is moved.

Some starters are equipped with a holding coil to keep the arm at the last contact point, and the rheostat is used only for starting. In other cases, the arm can be set in any position for speed regulation. The starting torque is cut down

considerably when a resistance starter is used, because the voltage drop due to the resistance converts most of the energy needed for starting into heat.

MAGNETIC PRIMARY-RESISTANCE STARTER. Figure 4-54 is an illustration of a magnetically operated resistance starter. Three resistance units are used in this starter. The diagram shows two sets of contacts. When the contacts marked *S* are closed, a resistance unit is placed in series with each line lead feeding the motor, thereby causing it to start slowly and on reduced voltage. After a definite time, another set of contacts, *R,* also close, cutting out the resistance and placing the motor directly across the line. An elementary diagram of this starter is shown in Figure 4-55. Its operation is as follows:

When the START button is pressed, the circuit is completed from L_1 through coil *S* to line L_2. Coil *S* is energized, closing the starting contacts, and the motor starts slowly. When the starting contacts close, the auxiliary interlock contacts also close to maintain a circuit through coil *S*. At the same time, the coil *TR* of a time-delay relay connected across *A* and *B* is energized, setting in motion a timing mechanism. After a predetermined time, contacts *TR* close, and a circuit is completed through coil *R*. This coil becomes energized and causes running contacts *R* to close. These cut out the resistance and connect the motor across the line. Pressing the STOP button opens all circuits through the holding coils, and thus all contacts to the motor are opened. Figure 4-56 shows a General Electric reduced-voltage, magnetic, primary-resistance starter. This magnetic primary resistor consists of a three-pole start contactor, a three-pole run contactor, a pneumatic timing relay, a single-step primary resistor, and two or three bimetallic overload relays.

Pressing the START button energizes the start-contactor coil. The start contactor closes, placing the motor on reduced voltage. The resistors in series with the line reduce the starting current drawn from the line. At the same time the timing-relay coil is energized, and after a definite time delay, the run-contactor coil is energized, closing the run contactors. The resistors are now bypassed, thus sending full voltage to the motor. Pressing the STOP button deenergizes all the contactors and stops all power to the motor.

A sustained overload will cause the heaters to become hot and will trip the overload contacts, opening the holding-coil circuits. To start the motor again, the overload contacts automatically reset or must be reset manually before the push-button circuits become operative. A dashpot and its operation and a timing mechanism are described under the heading of "Definite Mechanical Time Starter" in Chapter 7.

The two resistance starters just described place resistance units in series with the line and thereby reduce the voltage applied to the stator winding. These are called *primary*-resistance starters. The starting torque produced by a motor is comparatively low if this type of starter is used.

Secondary-Resistance Starter. If the resistance is inserted in the secondary or rotor circuit instead of the primary, the starting torque can be decreased consider-

ably. This can be accomplished by using a wound-rotor type of motor and by inserting resistance in the rotor-winding circuit.

The rotors of this type of motor have a three-phase wye-connected winding, the leads of which are joined to three slip rings located on the shaft of the rotor. The stator of this motor is connected across the line by means of either a triple-pole fused switch or an across-the-line magnetic starter.

The principle of operation is as follows:

If the three slip rings are shorted, the effect is similar to having a motor with a squirrel-cage winding. This motor will draw an excessive current if connected directly across the line. However, if the three slip rings are connected through three resistance units, a much lower current will flow through the line wires. The motor will start slowly, and, as it accelerates, the resistance is gradually cut out until the motor runs at full speed.

This type of motor is always started with the entire resistance in the circuit. In Figure 4-57, the manual switch is first thrown in, and then the handle on the resistance starter is slowly moved in a clockwise direction until all the resistance is cut out. This gradually increases the speed of the motor until it is running at full speed. These controllers are also made as speed regulators so that any desired speed can be obtained. Figure 4-58 shows a resistance starter that uses a magnetic switch for line connections.

Wound-rotor resistance starters are designed for magnetic operation as well as for manual control. An elementary diagram of a simple starter with two steps of acceleration is illustrated in Figure 4-59. In operation, pressing the START button energizes coils *S* and *TR*. This closes all *S* contacts, placing the stator directly across the line and the rotor in series with the resistance units. A timing mechanism of the dashpot, escapement, or other definite-time type, prevents time-delay contact *TR* from closing until a set time has elapsed, whereupon coil *R* is energized and contacts *R* close, cutting out the resistance of the rotor circuit. This brings the motor up to full speed. If the STOP button is pressed or, in the event of a prolonged overload, coil *S* is deenergized, the motor will stop.

Solid-State, Reduced-Voltage Starter. The solid-state starter, as shown in Figure 4-60, reduces the line voltage electronically during the starting of the motor and applies full voltage when the run cycle is energized. Conventional contacts are used for the run cycle, and the starting circuitry is then disconnected.

The voltage is reduced during the start by the controlled firing of the SCRs (refer to Chapter 10, Solid-State Motor Control). Part of the cycle is eliminated, as shown in Figure 4-61b. Figure 4-61a shows a normal sine wave. Eliminating part of the cycle results in a reduced current, which weakens the motor and limits the starting torque. The amount of current is adjustable and can be set according to the load requirements or line limitations. Once the control is set, it will allow a constant limited current to the motor until the start cycle is completed. This results in a timed start cycle. The motor will receive full voltage at a given time, regardless of the shaft speed.

A tachometer can be used on this type of control to govern the amount of time that the shaft takes to reach full speed. The tachometer is fastened to the motor and tells the control exactly what the shaft speed is. There are three adjustments necessary to customize the motor to the load when this control is used:

1. The amount of current to which the motor is limited as the load is brought up to speed.
2. The acceleration time. This adjustment may require the current limit (1) to be adjusted.
3. The breakaway torque adjustment. This part of the control will apply the maximum current allowed by the current-limiting control setting (1) until the shaft starts to move. Once the shaft starts to revolve, the acceleration control (2) applies the current needed to bring the motor up to the set speed in the given or set length of time.

This control can be purchased with the following protective features: (1) overload protection, (2) problems within the starting circuitry (if the motor is not up to speed within five seconds), (3) a signal if one of the motor leads is open, (4) low line voltage, (5) a signal if one of the power lines is open, and (6) a signal if the power lines are reversed.

Autotransformer Starters—Compensators. Although resistance starters are used to a great extent, autotransformer starters are much more satisfactory for reducing the voltage in the motor. The advantage is that the reduced voltage is accomplished by transformer action and not by a resistance, which wastes energy through heat.

The autotransformer is a coil of wire wound on a laminated iron core. Several taps are brought out to obtain different voltages. On the common type of compensator, three autotransformers, one for each phase of the line, are connected in wye, as shown in Figure 4-62. If each coil is tapped at the center and connected as shown to a three-phase motor, the voltage impressed will be one-half the line voltage. This is the manner in which the motor is connected when it is started. With this connection, the line current at start is considerably reduced.

On the ordinary compensator, two or three taps are usually brought out of the autotransformer so that different voltages can be applied to the motor at start. Whichever tap produces the most satisfactory starting torque at the lowest starting current should be used.

MANUAL AUTOTRANSFORMER STARTER. A typical manual autotransformer compensator is shown in Figure 4-63. It contains two sets of stationary contacts and a set of movable contacts. The movable contacts are mounted on an insulated cylinder to which a handle is attached.

When the motor is started, the handle is moved quickly in one direction. This connects the motor to the autotransformer so that it is started on a reduced voltage. After the motor accelerates, the handle is rapidly pulled in the opposite

direction. This disconnects the motor from the autotransformer and connects it directly across the line.

On nearly all manual compensators, the handle can be moved in only one direction at start, this direction being the one that starts the motor on a reduced voltage. It is necessary that the handle be moved quickly from the start to the run position; otherwise the motor will slow down as a result of the momentary open caused by the movement of the contacts from start to run. Most compensators have the contacts immersed in oil. This is done in order to extinguish quickly the arc that develops when the handle is thrown from start to run and thereby prevent the contacts from pitting.

Once the handle and contacts are in the run position, a holding coil connected across two terminals of the motor becomes energized and holds the handle in place. To stop the motor, a STOP button is pressed that opens the circuit in the holding coil, and this in turn releases the handle. Spring action returns the movable contact to its normal off position. If the voltage should fail or be reduced, the holding coil will be unable to hold the handle in the run position. If a prolonged overload should occur, the overload relay contacts will open and deenergize the holding coil. In order to restart the motor, it is necessary to reset the overload relay by pressing a RESET button. Figures 4-64 and 4-65 show the wiring diagrams of a manually operated, three-phase compensator.

In operation, the handle is thrown first to the starting position, causing the movable contacts to make contact with the stationary start contacts. This connects the motor through the autotransformer and starts it at a reduced voltage. After the motor accelerates, the operator pulls the handle back to the running position, and this connects the motor to the line. The holding, or undervoltage, coil is connected across two leads of the motor with a STOP button and overload relay contacts in series with it. To stop the motor, the button is pressed and the coil deenergized, causing the handle and movable contacts to spring back to the off position.

Compensators are also made with two autotransformer coils instead of three. Figure 4-66 shows a diagram of a two-coil compensator operating a three-phase motor. Its operation is as follows: When the handle is thrown to the start position, L_2 connects directly to the motor, and L_1 and L_3 connect directly to the autotransformers. Taps on the transformers are connected to the two other motor leads so that the motor starts on a reduced voltage. After it has accelerated, the handle is quickly thrown to the run position and is held there by the holding, or undervoltage, coil. Figure 4-67 shows the connection when the motor is starting. This is known as an *open-delta connection*.

MAGNETIC AUTOTRANSFORMER STARTER. Magnetic autotransformer compensators are essentially the same as the manually operated type just described, except that the contactors are closed magnetically and are also equipped with a timing device that connects the motor across the line after it has been running on reduced voltage for several seconds. An advantage of a magnetic compensator is

that it can be controlled by just pressing a button, which can be located at a convenient remote place. Figure 4-68 is a diagram of the motor and control circuit.

The magnetic autotransformer type of reduced-voltage starter is much the same in principle of operation as the magnetic primary resistor type, the difference being that a transformer is used in place of a resistor for reducing the line voltage to the motor during starting. This reduced-voltage starter has a three-coil autotransformer; three sets of contactors for the start, run, and wye contacts; a pneumatic timing relay; bimetallic overload relays (two or three); and an overtemperature unit to protect the autotransformer against overheating. The run and wye contactors are mechanically interlocked.

The operation of this starter (see Figure 4-69) is as follows: Pressing the START button energizes the start-and wye-contactor coils. The contactors for start and wye close, placing the motor on reduced voltage. The wye contactors connect the three coil ends of the autotransformers together to form the wye point. After a preset time interval, the pneumatic timing relay opens the wye contactors, and for a very short period of time the autotransformer acts as a reactor. The run contactors are then closed, placing the motor directly across the line. The transition from start to run is accomplished without opening the circuit to the motor; hence it is called a closed-circuit transition autotransformer starter. The starter is mechanically and electrically interlocked to secure the proper starting sequence. Pressing the STOP button or a sustained overload deenergizes all contactors and disconnects the motor from the line. Figure 4-70 is a typical wiring diagram of an Allen-Bradley autotransformer type of reduced-voltage starter. This is similar in many respects to the previous diagram. The time is located on and triggered by contactor $2S$. Note that the run and $1S$ contacts are mechanically interlocked.

Wye-Delta Starters. This method of reduced-voltage starting applies only to three-phase, delta-connected motors. If a delta-connected motor is connected across a 208-volt, three-phase line, each phase will receive 208 volts, as shown in Figure 4-71.

On the other hand, if the motor is reconnected in wye and the same line voltage is applied, each phase will receive 58 percent of 208, as shown in Figure 4-72.

To apply this principle to a controller, it is necessary to bring both ends of each phase out of the motor. The six leads can be interchanged when connecting from wye starting to delta running.

Manual or pushbutton magnetic controllers can be used to effect the change. Figure 4-73 shows a manual method of wye-delta starting by means of a three-pole, double-throw switch.

In starting, the main switch is first closed, and then the double-throw switch is closed for the starting position. Leads T_4, T_5, and T_6 are connected together when the switch is down, forming the wye point, and leads T_1, T_2, and T_3 are connected to the line. The motor starts rotating as a wye-connected motor, and each

coil group receives approximately 58 percent of its rated voltage. After the motor accelerates, the switch is closed in the running position, connecting T_2 to T_4, T_3 to T_5, and T_6 to T_1, which is a delta connection. The motor now runs normally.

Figure 4-74 shows a magnetic wye-delta starter of the *open transition* type. This term refers to the momentary disconnection of the motor from the line during the period of changeover from wye to delta connection. These starters are also made with closed transition. The closed transition is accomplished by placing the resistors at the disconnecting points during the transition, thereby keeping the circuits closed. The operation of the open transition type of wye-delta starter is as follows: Pressing the START button energizes contactors S, $1M$, and time delay TR. The S contactor connects motor terminals T_4, T_5, and T_6, and contactor $1M$ connects the incoming power lines to motor terminals T_1, T_2, and T_3, causing the motor to start as a wye-connected motor. After the time-delay relay times out, the timed-open (T.O.) contacts open, dropping out contactor S, and the timed-close (T.C.) contacts close, energizing contactor $2M$. The $2M$ contactor, upon energizing, applies the line wires to terminals T_4, T_5, and T_6, causing the motor to run at full voltage. Pressing the STOP button drops all contactors, stopping the motor. Contactors S and $2M$ are mechanically interlocked. Figure 4-75 shows another type of wye-delta starter.

Part-Winding Starters

Part-winding reduced-voltage starters are usually two-step accelerating starters for use with wye or delta part-winding-start motors. These motors were described in Chapter 3. The controllers described here are for use with wye-connected, part-winding-start motors.

The starters for the part-winding-start motors are constructed and wired so that part of the three-phase motor is energized first, and then the remainder of the winding is energized in one or more steps. The purpose of the starter is to reduce the initial inrush of current at the start. The motors used for part-winding starting may be the standard nine-lead, dual-voltage motor or the six-lead motor made especially for this purpose. If the standard nine-lead, wye-connected motor is used for this purpose, leads T_4, T_5, and T_6 should be wired together externally. Only the lower voltage can be applied to a dual-voltage motor.

Figure 4-76 is a wiring diagram of a nine-lead, wye-connected motor connected to an automatic part-winding starter. Connecting T_4, T_5, and T_6 together produces two wyes in the stator winding. Connecting T_1, T_2, and T_3 to L_1, L_2, and L_3 energizes half the winding. Connecting T_7, T_8, and T_9 to L_1, L_2, and L_3 completes the sequence, all windings being energized with both wyes in parallel. The control circuit operates as follows: Depressing the START button energizes the $1M$ contactor and the time-delay relay, TR, causing the motor to run on half the winding, T_1, T_2, and T_3. After the time-delay relay has timed out, contacts TR close, causing the $2M$ contactors to close, connecting the power to the second half of the winding, T_7, T_8, and T_9. The total motor current of the wye-con-

nected, part-winding type of motor is divided equally between the two sets of winding, with each winding handling half of full power.

Other wiring diagrams of a two-step accelerating starter for use with wye-connected, part-winding-start motors is shown in Figure 4-77.

Figure 4-78 shows a diagram that can be used for various part-winding schemes. This is a General Electric diagram for both wye and delta motors having nine or six leads. The table on the right shows the lead connections for the motors on the bottom of the drawing. Note the four and two-pole contactor arrangement.

Drum Starters

A manual drum type of controller, which can be used for starting or reversing small three-phase motors, is shown in Figures 4-79 and 4-80. This drum switch can also be used for split-phase and capacitor motors, as shown in Figures 4-81 and 4-82. Figure 4-83 shows typical connection diagrams of drum switches.

A switch of this type is used if the motor is located close to the operator, as on small lathes or other machine tools.

Figure 4-80 shows that when the handle is moved from one position to another, two line wires are interchanged, and the motor reverses. This switch can be adapted to reverse any small motor whether it is ac or dc. A complete description of this controller is given in Chapter 2.

Multispeed Starters

The speed of a three-phase motor can be changed by changing the number of poles in the motor. This may be done by reconnecting the motor so that the resulting number of poles is either twice or half the number of the original poles. This is known as a *consequent-pole connection*.

Two-speed motors that do not have a two-to-one speed ratio have two separate windings in the motor. When one or the other winding is connected to the line, the motor will run at different speeds because of the different number of poles in each winding.

Manual and magnetic starters are constructed in order to change the motor connections for different speeds, as in the case of the consequent-pole motor, and to change from one to another when two-winding motors are used.

All these starters employ overload protection in the form of thermal or magnetic relays. Some applications require that the motor be first started on slow speed and then, if so desired, raised to high speed. This is done by equipping the controller with a relay that will permit this sequence.

Other applications require that the motor be started on low speed and then automatically be connected on high speed only after a definite time has elapsed. This is accomplished by equipping the starter with a definite time relay.

The following two-speed magnetic starters will be described and illustrated:

1. Two-speed starters for two separate-winding motors.
2. Two-speed starters for consequent-pole-winding motors.

Two-Speed Starter for Two Separate-Winding Motors. Figure 4-84 shows a wiring diagram of a two-speed starter for operating a three-phase motor that has two separate windings. When the HIGH-SPEED button is pressed, coil hi is energized, causing contacts hi to close and thereby connecting the high-speed winding directly across the line. Auxiliary contact hi also closes and keeps coil hi energized after the HIGH-SPEED button is released. Pressing the STOP button causes the main contacts to open and stop the motor. The same result will be produced if coil hi is deenergized when an extended overload occurs.

If the LOW-SPEED button is pressed while the motor is running at high speed, coil hi will immediately become deenergized because of its interconnection with the contacts of the LOW-SPEED button. Coil lo will then be energized, and the low-speed winding is connected to the line.

Figure 4-85 shows a wiring diagram of a starter somewhat similar to that of Figure 4-84. This is for a two-speed motor with separate windings for each speed. Note that the slow-speed winding is marked T_1, T_2, and T_3 and the high-speed winding has terminal markings T_{11}, T_{12}, and T_{13}. The operation of this starter is practically the same as the previous starter. The motor can be started in either fast or slow speeds. The change from slow to fast can be made without first pressing the STOP button. When changing from fast to slow, the STOP button must be pressed.

Two-Speed Starter for a Constant-Torque Motor. Figure 4-86 is a wiring diagram of a starter that is used to change the speed of a two-speed, consequent-pole-winding motor with constant torque. Five contacts are used for high speed. Eight main contacts are needed for this type of controller.

The operation is as follows: When the LOW-SPEED button is pressed, a circuit is formed from L_1 through the STOP button, the normally closed high contacts (front contacts of the high button), low contacts (when pressed), the normally closed high interlocks, coil *S*, overload contacts, and to line *2*. Coil *S* is energized, and the motor starts and runs on low speed. The motor can be started at either the high or low speeds. The STOP button need not be pushed for changing speeds. The motor is connected in series-delta-consequent for low speed. For high speed, five main contacts are closed connecting the motor in two-circuit wye. (This starter can also be used for two-speed, variable-torque motors.)

Motor leads T_1, T_2, and T_3 connect together, forming the wye point of the two-circuit wye connection, and motor leads T_4, T_5, and T_6 are connected to the line. Figure 4-87 shows the control circuit for this motor.

Two-Speed Starter for a Constant-Horsepower Motor. This motor is connected in two-circuit wye for low speed and in series-delta for high speed. Figure 4-88 shows a complete wiring connection for a two-speed, constant-horsepower motor connected to a multispeed starter. Figure 4-89 shows a multispeed, consequent-pole starter.

Two-Speed Diagrams. Multispeed motor connections for two-speed motors are shown in Figure 4-90.

Adjustable-Frequency Controllers. The speed controllers discussed so far have varied the speed by varying the number of poles in the motor. As observed earlier, the speed of a three-phase motor depends on the number of poles and the frequency, or Hz. Adjustable-frequency controllers electronically adjust or determine the frequency according to the load requirements.

The adjustable-frequency controller first changes three phases into dc, and then, through electronic circuitry, changes dc back into three phases of any frequency from 0 to 200 Hz. The voltage usually varies with the frequency. The rule of inductive reactance applies in this case. Inductive reactance varies with the rate of change. More Hz means higher inductive reactance, and less Hz means less inductive reactance. Because inductive reactance is a form of resistance, the resistance of the motor will go up or down with the change in frequency. This makes it necessary to drop the voltage along with a drop in frequency. If the voltage is not dropped, the current can become excessive at a lower frequency. Ventilation also becomes important to the motor at lower speeds.

Many controllers are ordered from the manufacturer modified for a specific load requirement. Among the modifications available are the following:

1. Adjustable Hz control.
2. Reversing feature.
3. Dynamic braking.
4. Jog feature.
5. Controlled acceleration.
6. Controlled deceleration.
7. Overcurrent protection.
8. Undervoltage protection.
9. Reversed-phase protection.

The field repair of these controllers consists of replacing the complete circuitry boards. The manufacturer has a suggested list of replacement parts that should be stocked. Repairing the components requires an extensive knowledge of electronics. Figure 4-91 is a picture of an adjustable-frequency controller, and Figure 4-92 is a picture of one of the circuitry boards.

Quick-Stop AC Starters

In many motor applications, it is necessary to have a method of quickly stopping or braking the motor to ensure safe operation and to save time.

While a three-phase motor is coasting to a standstill, current is sent through it in a direction that will cause it to tend to reverse its rotation. The power is then immediately disconnected. This is called *plugging* and is accomplished by reversing the current through two leads of a three-phase motor.

To effect plugging, the instant that the motor circuit is opened, a new circuit is established that will reverse the motor. This will immediately stop it and cause it to run in the opposite direction. If the line is disconnected at the instant the motor comes to a full stop and is about to reverse its direction, then the motor will remain at a standstill.

To accomplish this, a plugging relay is used. The relay is mounted on top of the motor and is operated by a belt attached to the shaft of the motor. Contacts located inside the relay close when the motor is running but prevent operation in the reverse direction by opening as soon as the motor tries to reverse its direction. There are various designs in the construction of these relays, but essentially the operation of all of them is the same as that described.

A wiring diagram of a controller and plugging relay is shown in Figure 4-93. A reversing type of across-the-line starter is used. The simplified diagram of Figure 4-94 is traced in the following explanation of the circuit.

When the START button is pressed, coil F is energized and causes the three main contacts F to close and connect the motor across the line. At the same time, the normally open auxiliary contact F_1 is closed, maintaining the current through coil F. Also, the normally closed auxiliary contact F_2 is opened, thereby preventing current flow through the reverse coil R. The plugging relay contacts are closed by the rotation of the motor.

If the STOP button is pressed, coil F is deenergized, and it opens the line contacts to the motor, and contacts F_2 close, thereby completing a circuit through the plugging relay to coil R. This coil is energized and closes main contacts R, which cause current to flow through the motor in the reverse direction.

The motor immediately comes to a stop, and the instant it reverses its direction, it opens the relay contacts, deenergizing coil R. The main contacts R open and break the line circuit to the motor. This controller can be used for plugging in either direction.

There are several other methods that can be used for quickly stopping a three-phase motor. One of these is the application of low-voltage direct current to one phase immediately after the line switch to the motor is opened.

TROUBLESHOOTING AND REPAIR

In this section it is assumed that the motor and fuse are in good condition. To make certain that the motor is not at fault, connect a voltmeter at the motor

terminals and determine whether voltage is available when the contacts of the controller are closed. If there is no voltage, the trouble probably lies in the controller.

Because there are many different kinds and makes of controllers, a general procedure for locating the source of trouble is given.

1. If the motor does not start when the main contacts close, the trouble may be
   a. Open overload heater coil or poor connection.
   b. Main contacts not making. (It is not unusual for one or more contacts to wear sufficiently so that they will not make when closed. This will also occur if the contacts become dirty, gritty, or burned.)
   c. Broken, loose, or dirty terminal connection.
   d. Loose or broken pigtail connection.
   e. Open resistance units or open autotransformer.
   f. Obstruction on the magnet core, preventing the contacts from closing.
   g. Mechanical trouble, such as mechanical interlocks, gummy pivots, and poor spring tension.
2. If the contacts do not close when the START button is pressed, the trouble may be
   a. Open holding coil. (This can be tested by connecting a voltmeter across the coil terminals when the START button is pressed. If there is voltage when the START button is pressed, but the coil does not become energized, the coil is defective.)
   b. Dirty START-button contacts or poor contact.
   c. Open or dirty STOP-button contacts. (If more than one station is connected to the same controller, each station should be checked. If FORWARD-REVERSE stations are used and they are interlocked, check all contacts.)
   d. Loose or open terminal connections.
   e. Open overload-relay contacts.
   f. Low voltage.
   g. Shorted coil.
   h. Mechanical trouble.
3. If the contacts open when the START button is released, the trouble may be
   a. Maintaining contacts that do not close completely or are dirty, pitted, or loose.
   b. Wrong connection of station to the controller.
4. If a fuse blows when the START button is pressed, the trouble may be
   a. Grounded contacts.
   b. Shorted coil.
   c. Shorted contacts.
5. If the magnet is noisy in operation, the trouble may be
   a. Broken shaded pole causing chattering.
   b. Dirty core face.
6. If the magnet coil is burned or shorted, the trouble may be
   a. Overvoltage.
   b. Excessive current due to a large magnetic gap caused by dirt, grit, or mechanical trouble.
   c. Too-frequent operation.

TESTING COMPONENT CIRCUITS

By using a snap-around type volt ammeter-ohmmeter or individual instruments, many of the tests needed to determine opens, shorts, grounds, continuity, and the like may be conducted in a very short time. Shorted coils; open coils; grounded coils; open resistances; shorted resistances; low voltages; high voltages; excessive amperes; broken, loose, or dirty connections; and many other malfunctioning component circuits may be tested with comparative ease. This is true of all motors, as well as starters. Figure 3-183 shows one method of using this instrument.

A systematic procedure should be followed when troubleshooting controls. Extreme caution must be used when testing live components. When working on anything that should have the power off, always shut the power off yourself. Most disconnects have allowances for a padlock to be used to keep the power from being turned back on. It is very important to take this precaution. Controls with voltage above 240 volts should never be energized when troubleshooting.

The example used here will be a control operated by a remote switch, such as a float switch. It will be assumed that the device being controlled (a three-phase motor) is in good working order but is not receiving power. Figure 4-95 shows such a circuit.

The first thing to check is the line voltage. This is done by removing the cover of the control box and testing each line with a voltmeter. The volt readings should be taken between L_1 and L_2, L_2 and L_3, and then between L_3 and L_1. If full voltage is found, the power circuit should be visually checked for loose connections. These terminals include L_1, L_2, L_3, T_1, T_2, and T_3. Look for signs of heating at these connections. When a connection becomes loose, the terminal will become very hot, and the screw, wire, and terminal will become discolored or charred. All terminals should be checked and tightened if necessary. This should be done with the power off.

The control circuitry within the controller is checked next. Check this by looking at the control circuits given in the illustrations of this book. The external controls, the magnetic holding coil, and the normally closed overload contacts are always located between line 1 and line 2. Unless the control has been altered, line 3 is not part of the control circuit. Check also that the externally located controlling switches, such as the pushbutton, float, pressure, or limit switches, are connected between line 1 and the holding coil. The normally closed overload contacts are always located between the holding coil and line 2. A wiring diagram can usually be found in the cover of the controller. Now it has been established that the motor and line voltage are in working order. This narrows the problems to the control circuit and the chance that some component is open.

Opens can be located in the control circuit with a voltmeter. Connect one lead of the voltmeter to line 1, and touch the other lead to first one terminal of the holding coil and then the other terminal. There should be the same voltage reading that is read between line 1 and line 2. If the control-circuit voltage is

supplied with a transformer, the voltage read should be that of the transformer output. If there is no voltage on either side of the holding coil, the overload contacts are open. Pushing the RESET button should close the overload contacts. If they do not close and have had time to cool, they may be defective. In this case, they should be replaced.

If there is a voltage on one terminal of the holding coil but not the other, the coil is open. The coil must then be replaced.

If there is a voltage on both terminals of the holding coil, the coil and the overload contacts can be assumed to be in working order. To double-check these components, line 1 and the terminal marked 3 can be shorted out with a piece of wire. This will bypass the external control, and then the holding coil should close the contacts. A current-limiting resistor may be used in place of a wire. If the control functions, the problem will be in the external controlling device.

Solid-state controllers have very complicated circuitry, and so troubleshooting these units requires a good background in electronics and electric motors. These controllers will have repair instructions with them. Most of the repair consists of replacing boards or modules that plug into the circuitry. There is also a suggested list of parts that should be stocked for repairing purposes.

Chapter 5

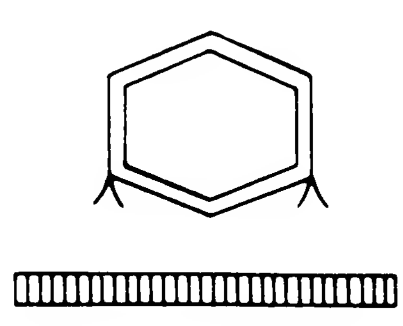
DIRECT-CURRENT ARMATURE WINDING

The complete process of armature winding requires a number of operations that are performed in sequence: (1) taking data while stripping the armature, (2) checking the commutator for shorts and grounds, (3) insulating the core, (4) making and taping coils, (5) placing the coils in the slots, (6) connecting the coil leads to the commutator, (7) soldering the leads to the commutator, (8) testing, (9) turning the commutator in the lathe, and (10) baking and varnishing. A form for recording this data is shown below.

DATA SHEET FOR D.C. ARMATURES

Make

K.W. H.P.	R.P.M.	Volts	Amps.
Cycle	Type	Frame	Style
Temp.	Model	Serial #	Phase

<table>
<tr><td>No. of Slots</td><td>Bars</td><td>Coils/Slot</td></tr>
<tr><td>Size Wire</td><td>Coil Pitch</td><td rowspan="3"></td></tr>
<tr><td>Center of Slot to</td><td>Center of Bars
Center of Mica</td></tr>
<tr><td colspan="2">Commutator Pitch
Lap Wave</td></tr>
</table>

When armatures such as those shown in Figure 5-1a, b, and c require rewinding, sufficient information must be gathered in the process of stripping to enable the mechanic to rewind it exactly as it was wound originally. Unless the different types of windings and connections are familiar to the mechanic, it will be almost impossible to record the necessary data. The different types of windings and connections will be described, and directions given for rewinding the more important ones.

TYPICAL WINDING FOR A SMALL ARMATURE

The simplest type of winding consists of a series of coils wound into the slots of an armature and connected in succession to the commutator. Figure 5-2a shows a diagram of this winding. The commutator is shown flattened for simplicity. A circular schematic diagram of the same winding is given in Figure 5-2b.

Insulating the Core. Before an armature is wound, however, the slots must be insulated to prevent the wires from touching the iron core and causing grounds. As in the other types of motors, the same kind and thickness of insulation is inserted as was removed. On a small armature, the insulation is cut so that it protrudes approximately 1/8 in. on both ends of the armature slot and about 1/4 in. above the slot, as shown in Figure 5-3. It is also necessary to insulate the shaft of the armature by placing several turns of insulating tape around it. Usually the end lamination is made of fiber that protects the coils from grounding. This is fitted over the shaft and extended outward to the bottom of the slots, as shown in Figure 5-4.

Winding Procedure

Small armatures, such as those used in vacuum cleaners and drills, can be held in one hand, as shown in Figure 5-5. Larger armatures are mounted between horses, as shown in Figure 5-6, or an armature holder is used, as shown in Figure 2-33b.

Assuming a nine-slot armature and data taken during the stripping process, the winding procedure is as follows:

Insert insulation in the slots. Choose any slot and call it slot *1*. Wind the required number of turns into the slots of the proper pitch or span, in this case 1 and 5, and then make a loop, as shown in Figure 5-7. Use enough tension on the wire to make a tight winding without breaking the wire. Make the loop at the end of the first coil and the beginning of the second coil. Start the second coil in slot *2* and wind the coil with the same number of turns as coil *1*. Be sure that the coil span is the same as coil *1*.

Make a loop when the second coil is finished, and then start winding in slot *3*. Continue in this manner until nine coils have been wound. Connect the end lead of the last coil to the beginning lead of the first coil. After the entire armature is wound, there will be two coil sides in each slot. Figure 5-8 shows a step-by-step winding of an armature having nine slots. Note that all coils have the same pitch and turns. This type of winding, in which a loop is made of the end of each coil, is called a *loop winding*.

Placing Wedges in the Slot. After the armature has been wound, the next operation is to close the slots so that the wires will not fly out while the armature is rotating at full speed. The procedure is illustrated in Figure 5-9. Note the

insulation between the coils in the slot. This may be a standard separator creased for better protection.

Cut the insulation so that it extends out of the slot about 3/16 in. Use a piece of fiber to press one side of the insulation into the slot and then the other side of the insulating strip into the slot. Slide a wooden (or fiber) wedge of the proper size into the slot over the insulation. On large armatures, the insulation is cut flush with the top of the slot and then banded.

Lead Swing

One of the most important operations in winding an armature is placing the coil leads in the proper commutator bars. Leads may be placed in the bars in any one of three different positions, depending on the original location. If a slot in the armature is viewed from the commutator end, the leads to the commutator may swing to the right of the slot or to the left, or they may be aligned with it.

The following method is used in determining the position of the leads in the commutator.

Stretch a piece of cord or string through the center of a slot, as shown in Figure 5-10. Note whether it is in alignment with a commutator bar or with the mica between the bars. If the data call for a lead swing of three bars to the right, place the lead of the first coil three bars to the right, counting the bar that lines up with the slot as No. 1. All the other leads follow in succession, as shown in Figure 5-11. If the center of the slot is in line with the mica, consider the bar to the right of the mica as bar No. 1.

Windings with More Than One Coil per Slot

In the armature so far discussed, the number of slots is equal to the number of commutator bars. This is not true of all armatures. Some have twice as many bars as slots, and it is not unusual for them to have three times as many bars as slots. In an armature of this type, the number of coils is always equal to the number of bars; therefore, an armature that has nine slots and 18 bars has 18 coils. The procedure in winding an armature of this type is exactly the same as for the simple loop winding, except that each slot has two loops.

Winding a Loop Armature with Twice as Many Commutator Bars as Slots. Assume a nine-slot, 18-bar armature. The procedure for winding this two-coil-per-slot armature is as follows: Wind the first coil into slots *1* and *5* in the same manner as in the simple loop winding. Make a loop and wind the second coil into the same slots. Make a loop and start the third coil in the slot *2*. Continue in this manner, winding two coils before going to the next slot. The windings should appear like those shown in Figures 5-12 and 5-13. There should be two loops for each slot. To distinguish between the first and second loops of each slot, sleeving of different colors may be put on the loops, or the second loop of each slot may

be made longer than the first. This procedure enables the winder to place the leads in the proper commutator bars without testing each lead.

LAP WINDINGS

Armature windings are classified in two main groups, lap and wave windings. The difference between them is the manner in which the leads are connected to the commutator bars. Lap windings may be classified in three ways: simplex lap winding, duplex lap winding, and triplex lap winding.

The simplex lap winding is one in which the beginning and the end leads of a coil are connected to adjacent commutator bars, as shown in Figure 5-14. Thus, the end lead of the first coil connects to the same commutator bar as the beginning lead of the second coil, and so on.

The duplex lap winding is one in which the end lead of a coil is connected two bars away from the beginning lead, as shown in Figure 5-15. Thus, the end lead of the first coil is placed in the same commutator bar as the beginning lead of the third coil, the end of the third in the same bar as the beginning of the fifth, and so on.

The triplex lap winding is one in which the end lead of a coil is connected three bars away from the beginning lead, as illustrated in Figure 5-16. Thus, the end of the first coil is connected to the same commutator bar as that of the fourth coil, the end of the fourth to the beginning of the seventh, and so on.

The simplex winding is most frequently used on small- and medium-sized armatures. Duplex and triplex windings are not employed to any great extent, but simplex windings can generally be reconnected as duplex or triplex windings when it is desired to run a motor on a lower voltage. Brushes used on duplex-wound armatures must contact at least two commutator bars, but brushes for triplex-wound armatures must touch at least three commutator bars.

The statement that any winding in which the beginning and end leads of the same coil are connected to adjacent bars is a simplex lap winding is true for any number of poles that a motor may have. To illustrate the lap winding, several types of armature windings will be described.

Lap Winding with Loops

A simple lap winding having one coil for each slot is shown in Figure 5-7. This nine-slot armature has nine coils, one for each slot. In this armature, the number of slots and commutator bars must be the same. The loops are connected to the commutator bars in succession, as shown in Figure 5-17.

A lap winding with two coils for each slot is shown in Figure 5-18. A nine-slot armature in this case has 18 coils. There must be twice as many commutator bars as slots, because there are 18 loops, and each loop requires one commutator bar. As illustrated, one loop is made short and the next one long, so that the leads may be put in the bars in the proper rotation.

Loop windings may also have three coils for every slot. It is then necessary to have three times as many commutator bars as slots.

Lap Winding without Loops

In a lap winding, it is possible to place the beginning lead in the proper commutator bar as each coil is wound and to connect all the end leads to the proper bars after the entire armature is wound. This requires the end lead of each coil to be left free until all the coils are wound.

Armature with One Coil per Slot

The procedure for winding and connecting an armature having one coil per slot follows:

Start in any slot and wind one complete coil in the slots of proper pitch. Place the beginning of coil *1* into the proper commutator bar, and leave the end lead free for connection after the armature is wound. Wind the entire armature in this manner, leaving all the end leads disconnected, as shown in Figure 5-19. After all coils are wound, connect all the top or end leads to the commutator. Place each top lead in the bar adjacent to the bottom lead of the same coil to produce a simplex lap winding like that given in Figure 5-20.

Armature with Two Coils per Slot

Simplex lap-wound armatures having two coils per slot are more common than those having one coil per slot. The procedure for winding this type of armature is as follows:

Start winding with two wires and place the beginning leads in the commutator bars according to the data taken. Cut the wires when the proper number of turns have been wound into the slots, and leave the end leads free, as shown in Figure 5-21. Start the next coil one slot to the left of the first coil as viewed from the commutator end. (When the coils proceed to the left, the winding is called *left-handed,* and to the right, *right-handed.*) Follow this procedure until all coils have been wound. Then place the top, or end, leads in the commutator bars in the proper succession. This is shown in Figure 5-22.

If it is difficult to identify the leads after all the coils are wound, the following method can be used to locate the proper top leads for correct connection. Use the test lamp as shown in Figure 5-23, and place one test lead on a commutator bar. Apply the other test lead to each free lead until one is found that causes the lamp to light. This lead must be placed in the commutator bar adjacent to the beginning lead.

Sleeving of different colors is sometimes used to identify the leads. One color is used for the beginning and end of the first coil, and another color for the second coil in the same slot; the third coil uses the same color as the first, and so

on. It will be necessary to test the first top lead, and then the colors will identify all the others.

Using short and long leads for the two coils in the same slot is another method of identifying the leads so that they can be connected properly.

Armature with Three Coils per Slot

Lap-wound armatures with three coils per slot are wound in the same manner as are armatures with two coils. Three bottom leads and three top leads are connected from each slot. These leads are placed in consecutive commutator bars, as was done in the case of the two-coil-per-slot windings, and the leads are similarly identified. Figure 5-24 shows three coils in one slot.

Coil Windings

The windings discussed thus far are hand windings in which the turns are wound into the slot one by one. This method is used on the small armatures, but on large armatures (and on a few small ones) the coils are wound on a form and then placed in the slots as a complete unit. The leads of a coil-wound armature are connected to the commutator in the same way as are those of a hand-wound armature. Figure 5-25 shows several coils of a coil-wound armature with two coils per slot.

WAVE WINDINGS

There are three groups of wave windings, namely, simplex wave winding, duplex wave winding, and triplex wave winding.

The difference between a wave winding and a lap winding is in the position of the armature leads on the commutator. In the simplex lap winding, the beginning and end leads of the same coil are connected to adjacent bars. In the wave winding, the beginning and end leads of a coil are connected to commutator bars quite far apart. Thus, on a four-pole motor they are connected on opposite sides of the commutator; on a six-pole they are connected one-third of the commutator bars apart; and on an eight-pole motor, one-fourth the bars apart. A wave winding is one in which the beginning and end leads of a coil are connected a definite number of commutator bars apart, depending on the number of poles in the motor and the number of bars on the commutator. In a lap winding, the leads face one another, as shown in Figure 5-26. In wave winding, the leads face away from one another, as shown in Figure 5-27.

In a wave winding for a four-pole motor, the current must travel through at least two coils before reaching a bar adjacent to the starting point. For a six-pole motor, the current will travel through three coils before reaching an adjacent bar. Two-pole motors cannot be wave wound.

Commutator Pitch

The number of bars between the coil leads is called the *commutator pitch,* usually written c.p. Thus,

$$\text{c.p.} = \frac{\text{no. of commutator bars} \pm 1}{\text{no. of pairs of poles}}$$

Assuming a four-pole, 49-bar armature,

$$\text{c.p.} = \frac{49 \pm 1}{2} = 24 \text{ or } 25 \text{ bars}$$

Usually the number of bars is expressed as 1 and 25 or 1 and 26. Thus, if the commutator pitch is 24 bars, the leads are placed in bars *1* and *25,* as shown in Figure 5-28. If the commutator pitch is 25 bars, the leads are placed in bars *1* and *26.* It is important to remember at this point that all four-pole, wave-wound armatures must have an odd number of commutator bars. Six-pole motors can have an even or odd number, and eight-pole motors must have an odd number of bars. All two-pole motors are lap wound. Read the section in Chapter 2 on "Rewinding a Wave-wound Armature," page 79.

Retrogressive and Progressive Windings. According to the formula, the commutator pitch may be either of two figures. If the smaller number is used, the motor will run in one direction; if the larger number is used, the armature will rotate in the opposite direction. These connections are known as retrogressive and progressive windings, respectively, and they are used in both lap and wave windings. A simplex progressive lap winding is one in which the current flowing in a coil terminates one bar beyond the starting point. This type is shown in Figures 5-29 and 5-31. A simplex retrogressive lap winding is one in which the current flowing in a coil terminates one bar before the starting point. This type appears in Figures 5-30 and 5-32.

If a progressive connection is changed to a retrogressive connection, the armature will rotate in the opposite direction.

Assuming a four-pole motor, a simplex progressive wave winding is one in which the current flowing through two coils in series terminates one bar beyond the starting point. A four-pole, simplex progressive wave winding is shown in Figures 5-33 and 5-35.

A simplex retrogressive wave winding is one in which the current flowing through two coils in series terminates one bar before the starting point. This type is shown in Figures 5-34 and 5-36.

Connections for a progressive lap winding with two coils per slot are shown in Figure 5-37. Several coils of a retrogressive lap winding are shown in Figure 5-38.

Connections of both types of wave windings of 23-slot, 45-bar armatures with two coils per slot are shown in Figures 5-39, 5-40, 5-41, 5-42, and 5-43a.

Connections for a circular diagram of a four-pole, wave-wound armature are shown in Figure 5-43b. The stator poles are shown by the dotted lines. An *X* marks each pole center of the armature. Figure 5-43c is a circular diagram of a six-pole, wave-wound armature.

Equalizer Connection. Equalizer connections, also known as *cross-connections,* are used in large dc armatures to minimize circulating currents. These circulating currents are usually due to uneven air gaps between the field poles and the armature and may be eliminated by connecting together commutator bars of equal potential. The bars to be connected together depend on the number of poles in the motor and the number of commutator bars. Because equalizer connections are used mostly on repulsion motors, this subject was discussed in more detail in Chapter 2. It should be understood that equalizer connections are used on lap windings only.

REWINDING PROCEDURE

Taking Data

During the process of stripping an armature, sufficient information should be recorded to enable the winder to rewind it properly. The following procedure is used in many shops:

Count the slots and commutator bars. Record the lead throw by marking the slots and commutator bars of a coil, as shown in Figures 5-44, 5-45, and 5-46. The marks shown in the diagrams are made with either a file or center punch. These record both the coil pitch and the lead throw. This is an important operation, as a wrong lead throw will cause sparking and poor operation. Take the coil pitch at the same time. If the coil is wound in slots *1* and *8*, record the pitch as 1 and 8. If the armature is form wound, several coils will have to be lifted. Record the end room by measuring the distance that the coils extend beyond the ends of the slots.

Determine the number of coils per slot and kind of winding, that is, hand, form, loop, right-hand, left-hand, clockwise, and so on. Count the number of turns in each coil. If this is too difficult, cut the coil and count the cut ends of the wires.

If it is a one-coil-per-slot winding, it may be necessary to count all of the turns in a slot and then divide by 2 in order to obtain the number of turns in each coil. If it is a two-coil-per-slot winding, divide the total number of turns in a slot by 4 to obtain the number of turns per coil. On large armatures, preserve one coil in order to have the size for the construction of a form for the new coils. Determine the size of the wire by means of a wire gauge or micrometer. Also record the wire

covering, such as single-cotton-enamel, Formvar, or whatever has been used. Record the kind of insulation in the slot.

Caution. Try not to disturb the laminations. Do not break the end-fiber insulators. Make sure that all the insulation is removed from the slots. Unsolder the leads from the commutator, and if the ends break off at the bars, use a hacksaw blade to force the broken particles of copper out of the bar. Use a blade that will make a cut in the bar no larger in size than the diameter of the new wire. A tool for this purpose is shown in Figure 5-47.

Stripping the Armature

Usually the wedges are tight in the slots, and so their removal is difficult. Place the teeth of a hacksaw blade on the wedge, as shown in Figure 5-48, and tap it with a hammer so that the teeth are embedded. The blade is next tapped on the end to embed its teeth more deeply in the wedge and at the same time to drive the wedge out of the slot. On large coilwound armatures, stripping is relatively simple. Cut the bands and pry out the coils one by one after disconnecting all leads from the commutator. On the smaller armature with semiclosed slots, and especially if they are hard baked, it may be necessary to place this armature in a burn-off oven to soften all of the insulation and varnish. If this is done, it will be necessary to first remove the commutator from the shaft. Disconnect all wires from the commutator by cutting them either with a hacksaw blade or with a cutting tool in the lathe. It is presumed that all lead data have already been taken. Also, cut the wires from the front of the armature slots, using the tools as above. This should allow ample room to remove the commutator from the shaft using either a pulley remover or a hydraulic press. It is important that exact measurements be taken of the distance from the commutator to the end of the shaft (Figure 5-49). Alignment of commutator to slot must also be known (Figure 5-10).

After the commutator is removed, the armature is heated sufficiently, using the burn-off oven, to soften or char the insulation. If an oven is unavailable, it may be possible, after cutting the wires on one end of the armature, to pull them out from the other end. The commutator may be put back before or after winding the armature, depending on the method of winding and connecting.

Caution. Press the commutator on the exact distance measured before removal. The commutator must fit firmly to prevent movement during rotation. Use a press for reinstalling the commutator. Check the commutator for grounds and shorts before winding the armature.

Soldering the Commutator

After reinsulating and rewinding the armature and placing the leads in the commutator, the next step is to solder the leads with either a gas or an electric

soldering iron. Electric irons are generally used on small armatures and gas irons on the large ones. The size of the iron used depends on the size of the commutator. Leads can also be welded to the commutator or soldered by means of a torch.

The procedure is as follows: Place soldering flux over each wire in the commutator bar. Place the tip of the soldering iron on the commutator, as shown in Figure 5-50, and wait until the heat from the iron is transferred to the area of the commutator bar that is to be soldered. This heat transfer occurs when the paste starts bubbling.

Place solder on the commutator near the iron and allow it to melt and flow into the commutator slot before removing the iron. Flow the solder entirely around the leads. To prevent the solder from flowing down the back of the commutator and causing short circuits, raise one end of the armature so that solder flows forward. To prevent the solder from flowing from one bar to another, the iron is held as shown in Figure 5-51. Wipe off all excess flux after the soldering is completed.

Banding the Armature

Bands are used on armatures to hold the commutator leads in place. A cord band is used on small armatures to prevent the leads from flying out of the slots while the armature is rotating. Large armatures have steel bands for the same purpose. For large armatures having open-type slots, use steel or tape bands to prevent the coils from flying out of the slots.

Cord Bands. The procedure for placing a cord band on an armature is shown in Figure 5-52, and the following directions should be observed: Use the proper size of banding cord—heavy for larger armatures, light for small armatures. Start at the end nearest the commutator and wind several turns in layers, allowing about six inches of the beginning to be free. After winding several turns, loop the start, as shown at *3* on the diagram, and wind several more turns over the loop. Bring the end of the cord band through the loop and then pull on the free end. This will pull the end under the cord band and secure it there, at which point the cord can be cut off. Use enough pressure in winding so that the band will be tight.

Steel Bands. Some open-slot types of armature require steel bands to prevent the coils from flying out of the slots while the armature is rotating. Steel bands are placed on the front and back ends of the coils. These bands are put on the armature in a different manner than are the cord bands. The procedure is illustrated in Figure 5-53 and is as follows: Place the armature in a lathe and place mica or paper insulation in the band slot around the entire armature to insulate the band from the coil sides. Hold the insulation in place by tying a turn of cord around it. Place small strips of tin or copper under the cord, equidistant around the armature, in order to secure the band after it is wound. Use the same-gauge steel-band wire as on the original band.

Steel bands must be put on the armature with much more pressure than is needed for cord bands. It is therefore necessary to utilize a device called a *wire clamp* to provide the required pressure. This device consists of two pieces of fiber fastened together by means of two screws and two wing nuts. The steel-band wire is fed through this clamp to the armature. Secure the clamp to a lathe or bench so that it can be held stationary while the armature is being banded. Feed the wire to the armature through the clamp while slowly turning the armature. Take care not to put too much pressure on the wire; otherwise it will break. After one band is placed on the coil, turn the copper or tin strips over and solder the entire band. Proceed to the next band.

Tape Bands

Many shops are now using a woven glass tape treated with a polyester or epoxy resin rather than a steel banding wire. The tape is applied to armatures or rotors at about the same tension as with steel wire, using a tape tension device for applying the tape. It is preferable that the armature be hot before applying the tape to eliminate voids between layers. Approximately 50 lb. of tension can be used, and as many as five layers can be applied in an overlapping manner. The tape is held in place by smoothing it down with a hot soldering iron. It is sealed and fused at the end while under tension before it is cut off. The iron is also used to fuse layer to layer. After banding, the armature is dipped into a compatible varnish and dried. It is then baked for several hours to cure. Figure 5-54 shows a tension device for applying glass band tape.

Testing the New Winding

After the rewinding and connections are completed, it is important that both winding and connections be tested for shorts, grounds, open circuits, and correctness of connections. This must be done before varnishing the winding so that any troubles that are found may be corrected more readily. Detailed instructions for making these tests will be found later in the chapter under "Troubleshooting and Repair."

Baking and Varnishing

After the armature has been wound, soldered, banded, and tested, the next operation is varnishing. This process makes it moistureproof and prevents vibration of the coils of wire in the slots. Vibration has a tendency to impair the insulation on the wires and cause shorts. Moisture also will cause the insulation on the wires to deteriorate.

Armatures may be varnished with either baking varnish or air-drying varnish. Air-drying varnish is applied to the armature when baking is undesirable or inconvenient. Baking varnish is more effective because of the moisture that can be eliminated only by baking.

When using baking varnish, tape the shaft and commutator to prevent the varnish from adhering; otherwise, scraping will be necessary after the varnish hardens. Follow the baking instructions for the varnish being used.

Balancing the Armature

Armatures should be tested for mechanical balance after they are varnished. Undue vibration and unusual noises may be due to an imbalance in an armature and should always be investigated immediately. Therefore, it is important that the armature be balanced before it is installed in the motor. Balancing ways are used for this purpose and may be of the type shown in Figure 5-55. These are built in various sizes. The method of balancing an armature using this machine or others similar to this is as follows: Place the armature on the balancing ways and roll it gently. When it comes to a stop, the heavier point will be on the bottom. To compensate for this heavy point, it is necessary to counterbalance it with weights diagonally opposite the heavy point. This should be directly on top. The top slot or slots should be marked. Make this test several times. If the marked slot does not come out on top, the armature may be balanced. If the marked slot always comes to rest at the top, then it is necessary to counterbalance the heavy point on the bottom. This is accomplished by placing a lead, brass, or copper strap under, above, or in place of the wedges in the marked slot or under the bands of the armatures. Experience will determine the amount of metal necessary to balance the armature. This method of balancing is called *static balancing*. Another method is called *dynamic balancing* and requires a machine usually complicated in design.

TROUBLESHOOTING AND REPAIR

Testing

Before attempting to wind the armature, the usual procedure is to test the commutator. This is done to facilitate repairs in case the commutator is defective. The commutator is tested for grounded bars and shorted bars.

Test for Grounded Commutator. A commutator is grounded when one or more bars contact the iron core of the commutator. Use the test leads and lamp connected as shown in Figure 5-56. Attach one test lead permanently to the shaft of the armature and the other test lead to a commutator bar. If the bar is properly insulated, the lamp will not light. There should be no sparking or arcing between the bar and the ground. Place a test lead on the next bar and test in the same manner as before, continuing until all bars are tested. If the lamp lights when a bar is touched, a ground is indicated.

Test for Shorted Commutator. The test illustrated in Figure 5-57 is made to reveal defects in the mica between the bars. Place one test lead on a commutator bar and the other test lead on an adjacent bar. No light should be visible on the test lamp. If a light is observed, a short exists between the bars contacted by the test leads. Move each lead one bar over, and test as before. Continue in this manner until all bars have been tested.

Testing the Winding. After an armature is wound and the leads connected to the commutator, tests should be made in order to reveal defects that may have occurred during winding. These tests are to determine grounds, shorts, opens, and reverses in the windings and are made by using either a growler or millivoltmeter.

Test for Grounds. After rewinding an armature, the first step is to determine whether or not the winding is grounded. A simple test lamp is all that is necessary. This can be done as shown in Figure 5-58, before the leads are connected to the commutator. If the test is to be made on an armature whose coils are connected to the commutator, the test circuit becomes that of Figure 5-59. If the lamp lights and the coils are not connected to the commutator, a grounded winding is indicated, and the condition should be remedied before further tests are made. The exact position of the ground must be found in order to remove the cause. The winding usually grounds at the corners of the slots, where there is a sharp bend in the coil, or inside the slots, if there are sharp laminations out of place. If the coils are connected to the armature and the lamp lights, either the armature winding or the commutator may be grounded.

The procedure for locating the ground is as follows: Inspect the coils at the slot ends and look to see whether the slot insulation has shifted and caused the coils to touch the iron core, as shown in Figure 5-60. In a new winding, the insulation may be shifted back to position. However, if this cannot be done, a new piece of insulation should be inserted at the bad spot. If the ground cannot be located by inspection, the growler or meter test should be made.

BAR-TO-BAR METER TEST. The circuit of Figure 5-61 is used with a low-voltage source of direct current, such as a battery or 115-volt line, with one or several lamps in series with it, as shown in Figure 5-62. Tie several turns of cord around the commutator and put the test leads under the cord, as shown in Figure 5-63. Place one lead of a dc millivoltmeter on the shaft and the other lead on a commutator bar. The meter needle should deflect if there is a ground. Move the meter lead from one bar to another until the meter shows little or no deflection. The coil connected to this bar is the grounded one. Figures 5-64 and 5-65 show schematic diagrams of this test circuit.

Caution. On a two-pole motor, the current leads may be placed on opposite sides of the commutator or any fraction thereof. Meter readings are taken on bars

between these leads. On a four-pole motor, the leads should span one-fourth of the number of bars; on a six-pole motor they should span one-sixth of the number of bars; and so on. Allow only enough current to flow through the armature to permit a deflection of approximately three-fourths of full scale. This is accomplished by varying the number of lamps switched into the circuit or the battery voltage used.

A GROWLER TEST. A growler, shown in Figure 5-66, is a device that is used to detect and locate grounded, shorted, and open coils in an armature. It consists of a coil of wire wound around an iron core and is connected to a 120-volt ac line. The core is generally H shaped and cut out on top so that the armature will fit on it, as shown in Figure 5-67. When alternating current is applied to the growler coil, voltage will be induced into the armature coils by transformer action.

The procedure for testing an armature for grounds by using the growler is as follows:

Place the armature on the growler and turn on the current. Place one lead of an ac millivoltmeter on the top commutator bar. Place the other meter lead on the shaft, as shown in Figure 5-68. If a reading is noticed on the meter, turn the armature so that the next commutator bar is on top, and test as before. Continue in this manner until a bar is reached that gives no deflection, thus indicating that the grounded coil is connected to this bar.

THE TRIAL TEST. A grounded coil may be located without using either the growler or the bar-to-bar test. For lap windings the method is as follows: Disconnect two leads from commutator bars on opposite sides of the commutator and separate them, as shown in Figure 5-69. Use a test lamp and determine which half of the winding is grounded. This is done by touching one test lead to the shaft and the other to the disconnected leads. Whichever causes the lamp to light is the grounded side of the winding, and so the other half is eliminated.

Disconnect one commutator lead from approximately the center of the grounded side of the armature, as shown in Figure 5-70, and test as before. This procedure immediately eliminates three-fourths of the winding. Continue in this manner until the grounded coil is located by the process of elimination.

REPAIR OF A GROUNDED COIL. After the grounded coil has been located, it becomes necessary to determine its cause and to repair it if possible. The usual cause is a breakdown in the slot insulation or a lamination pressing into the coil at some point. If the source of trouble is visible, it may be possible to remedy the trouble quickly by inserting new insulation where needed or by properly positioning the lamination. If the trouble is not visible, it is necessary to rewind and reinsulate part or all of the winding or to eliminate the offending coil from the circuit. The first method is used if the entire winding is desired in the circuit. Other factors, such as time, expense, and type of shop, will determine the use of the second method.

The second method involves the following steps: Disconnect each lead of the grounded coil from the two commutator bars. Connect a jumper between these bars to short them. Figures 5-71 and 5-72 show how to remove a loop-wound coil from the circuit. Figures 5-73 and 5-74 show, respectively, how to remove a lap and a wave coil from the circuit.

Although this procedure allows the grounded coil to remain in the armature, it results in electrical removal of the coil from the armature circuit. The disconnected coil leads are taped and allowed to remain in their original position without touching the commutator. If the coil is grounded in two places, cut it through to prevent induced currents. To determine whether or not there is a double ground, place the armature on a growler and test for shorts.

Tests for Shorted Coils. Shorted coils in a new winding usually can be attributed to excessive pounding on the coils, especially if a tight winding is made. These shorts occur when two turns of one coil make electrical contact, when one coil makes electrical contact with an adjacent coil, and when the coil sides in the same slot are shorted (short on the half).

GROWLER TEST. The procedure to test for short circuits in an armature is as follows: Place the armature on the growler and turn on the current. Hold a thin piece of metal, such as a hacksaw blade, over the top slot of the armature, as shown in Figure 5-75. The blade should be held so that it is directly over the slot and along the length of it. If the coil in this slot is shorted, the blade will vibrate rapidly and create a growling noise. If the blade remains stationary, it is an indication that no short exists in the coil under test. After several top slots have been given the hacksaw blade test, turn the armature so that the next few slots are on top. Test as before and continue this procedure for the entire armature.

If the armature is very large, the growler can be placed on top of it and tested in the same manner as before. Some shops have the growler mounted sideways, with a provision to move it up or down. The armature in this case is mounted on horses adjacent to the growler during the test.

An internal growler such as used for stators may also be used for armatures. These are made with or without a built-in feeler. The growler with the built-in feeler has a flexible blade attached to the growler so that a hacksaw blade or similar instrument is not necessary. This type is especially desirable in smaller stators that have no room for a separate feeler. Figure 5-76 shows an internal growler with a separate feeler used on a larger armature. A short circuit in the coil under the growler will cause the hacksaw blade at the other side of the coil to vibrate.

An armature having cross-connections or equalizers cannot be given the hacksaw blade test. This type of armature will cause the blade to vibrate at every slot, which would seem to indicate that possibly every coil is shorted. This is not the case, however, and it will be necessary to give this type of armature a meter test.

A shorted coil on either a lap- or wave-wound armature will cause the blade to vibrate over two slots, thus identifying the slots in which the shorted coil slides are located. These slots should be marked with a piece of chalk. If vibration occurs over more than two slots, the possibility exists that more than one coil is shorted. On a four-pole wave winding, the blade will vibrate at four spots if the short is *between two adjacent bars*. On a six-pole wave winding, there will be six points at which the blade will vibrate.

On a lap or wave winding, it is simple to trace the leads of the defective coil and see where they are connected to the commutator. In the case of the wave winding, it is a little more difficult, and therefore a meter must be used for tracing. This is especially true if two commutator bars are shorted.

Figure 5-77 shows a growler with test prods and a meter for testing for grounds, shorts, or opens. The test for shorts is described above.

BAR-TO-BAR METER TEST. Direct current is generally used for this method of finding the shorted coil. Directions are as follows: Place the armature on horses and connect a source of direct current to the commutator, using the circuit of Figure 5-78. Place the leads of a dc millivoltmeter on adjacent bars, beginning at bars *1* and *2*, and permit enough current to flow through the armature to give about three-fourths of full-scale deflection on the meter. If the coil connected to these bars is in good condition, a normal deflection will be observed on the meter. Move the leads of the meter to the next two bars—*2* and *3*—and observe the reading. The meter needle should deflect the same amount as before. If the reading is less or zero, a shorted condition exists in the coil connected to these bars.

Caution. A slightly lower reading will result if one coil has less wire than the others do. In the loop winding and other windings that are put in the slots as a unit, the meter readings will be slightly different, as the readings are taken around the commutator. The reason for this is that the coils become larger as they are put one on top of the other. To determine whether the lower reading indicates a short, place the armature on the growler and test it for shorts. If it tests perfectly on the growler, then the lower reading means less wire or a shorter coil. On a four-pole wave winding, a shorted coil will be indicated by approximately one-half the normal reading and will be revealed on opposite sides of the commutator.

Eliminating a Shorted Armature Coil. If there are more than one or two shorted coils on an armature that has seen many years of service, the best procedure is to rewind the armature. This is advisable because the armature coils have probably been heated to such a degree that the insulation is brittle and charred, and handling on the bench would cause more shorts. If one or two coils are shorted and the rest of the armature seems to be in good condition, these coils can probably be cut out of the circuit without seriously impairing the motor's effi-

ciency. The method employed for cutting out shorted coils depends on the type of armature.

Cutting a Shorted Coil Out of a Loop-wound Armature. Assuming that the shorted coil has been located, the next step is to cut the turns of the coil at the end of the armature opposite the commutator. Be sure that every turn in the coil is cut to prevent induced currents from circulating in the shorted coil and causing damage to other coils.

Cutting the coil will cause an open circuit in the winding. Because the bars that connect to the defective coil are known, the open can be repaired by connecting these bars together with a jumper. Figures 5-79, 5-80, and 5-81 show the circuits formed by this method for a loop, a lap, and a wave winding. Figure 5-82 is another view of Figure 5-81.

Another method of cutting out a coil consists of cutting the coil, as was just shown, and twisting together the turns of first one side and then the other. Make sure that the wires do not have any insulation on them before they are twisted. With this procedure it is not necessary to put a jumper on the commutator, nor is it necessary to touch the commutator for any reason.

These methods of cutting out coils are not strongly recommended because the coil may be located on the bottom of the slot and therefore very difficult to reach for cutting purposes. In addition, damage may be done to other coils in the process of cutting out the defective one.

Therefore, such methods are suggested only for extreme conditions when the time element or the need for a temporary repair makes them useful.

CUTTING OUT A SHORTED COIL ON A MEDIUM-SIZED LAP WINDING. On this type of armature it may be possible to reach the coil that must be cut, but it may be impossible to cut out only the defective coil. The procedure is exactly the same as in the case of the loop winding shown in Figure 5-79. In all these cutting operations, experience determines the proper procedure to be used.

CUTTING OUT A SHORTED COIL ON A WAVE-WOUND ARMATURE. In a four-pole, wave-wound armature, the leads of any coil are connected approximately on opposite sides of the commutator. Therefore, if a shorted coil is cut open, it will be necessary to place a jumper between the two bars that were joined to the defective coil. This means that a jumper must be placed in bars on opposite sides of the commutator, as shown in Figures 5-81 and 5-82.

When a four-pole, wave-wound armature is given a bar-to-bar meter test, a shorted coil will be indicated on the meter on opposite sides of the commutator. This does not mean that two coils are shorted but that the defective coil is in the circuit twice, as in a four-pole wave winding, the current flows through two coils in series reaching an adjacent bar.

Test for Open Circuits. Open circuits in an armature may be caused by a poor connection of leads in the commutator bars or by a broken wire in an armature

coil. In either case, such a condition will cause sparking at the brushes. Poor connections and broken wires can often be detected visually. When this is not possible, other means must be used to locate the open.

Bar-to-Bar Test. Set up the armature and test with the millivoltmeter across bars, as shown in Figure 5-83. No readings will be indicated on the meter until the meter leads are bridging the two bars to which the open coil is connected. At this point the meter needle will jump violently, and precautions must be taken to prevent it from bending or breaking.

Repair of an Open Coil of a Lap Winding. The method of repair of an open coil depends to a great extent on the time allotted for the repair, the type of armature that is being repaired, and the kind of work in which the particular shop specializes. Of course, if one or more coils are open, the proper procedure is replacement. Usually rewinding of the armature is necessary. The next best method is to jump the two commutator bars that test open by soldering a piece of wire into the slots of the two bars. The circuit formed is shown in Figure 5-84. This is the only method that can be used in many cases. Another way of jumping two adjacent bars is to scrape away some of the mica between them and wedge a piece of wire in the slot. The wire is then soldered to the bars.

Repairing an Open Coil of a Wave Winding. When a wave winding is tested with the meter, the procedure is the same as that used for the lap winding. Because each coil on a four-pole, wave-wound armature is connected to bars on opposite sides of the commutator, an open coil is jumped, as illustrated in Figure 5-85. A method that requires less effort and time but that necessitates the removal of two coils instead of one, is often satisfactory. The procedure, shown in Figure 5-86, is to jump the two adjacent bars that test open. This does away with the long jumper from one side of the commutator to the other.

Growler Test for an Open Coil. To locate an open coil with a growler, set up the armature on the growler in the usual manner. Test the top two adjacent bars with an ac millivoltmeter. Rotate the armature and continue testing adjacent bars. When the millivoltmeter bridges the two bars connected to the open coil, the meter pointer will not be deflected. All other bars will give a deflection. This test for an open coil can be made without the meter by shorting the top two bars with a piece of wire, as shown in Figure 5-87. Absence of a spark indicates that the coil is open. The open may be either at the commutator bar or in the coil itself. This procedure may be used to determine the location of the leads of a shorted coil. However, the hacksaw blade test is the most satisfactory method of determining a shorted coil.

Test for Reversed Coils. Reversed coils occur only on armatures that have been newly rewound and result from placing the leads in the wrong commutator bars. The method of locating the reverses differs with the various types of windings.

Bar-to-Bar Test in a Loop Winding. Set up the armature for a bar-to-bar test. When the meter leads are placed on the two bars that connect to a reversed coil, as shown in Figure 5-88, a reversed reading will be indicated on the meter. When the meter is placed on the two bars in front of the reversed coil and the two bars behind the reversed coil, double readings will show up. As Figure 5-89 illustrates, if two loops are reversed in a loop winding, a double reading will be obtained; next a reversed reading; and then a second double reading. All others should be normal.

Bar-Magnet Test. To check for a reversed coil on other than loop windings, a bar magnet is moved over each slot, inducing current in the coil lying in that slot. If a meter is connected to the two bars of that coil, as shown in Figure 5-90, the pointer will move. If there is a reversed coil on the armature, the induced current will flow through the meter in the opposite direction and cause a reversed reading.

Another method is shown in Figure 5-91. If direct current is passed through the winding and a compass is held alongside each coil in succession, the compass needle will reverse when the compass reaches the reversed coil.

Commutator Repairs

The various parts of a commutator are shown in Figure 5-92. They include a number of commutator bars, an equal number of mica segments, and an iron core consisting of two end rings and a connecting shell on which the bars and mica segments are placed.

The commutator bars are made of high-grade copper and are shaped as shown in Figure 5-93. They are wedge shaped, the larger width being on top. Toward the bottom, the bars are partly cut out on both sides in the shape of a V. Rings fit these V cuts to hold the commutator together. Individual commutator bars are seldom replaced because the job is impractical.

Mica segments are used between bars to prevent adjacent bars from touching, and it is often necessary to replace them. The segments are cut from sheet mica of the proper thickness and are placed between the bars. When these are replaced, the segments must be the same thickness as the original mica; otherwise the commutator will be either too loose or too tight.

The end rings are made of iron and are called *V rings*. These are insulated with mica and are called *mica V rings*. The rings fit into the V cuts on the commutator and hold all the bars together. On one type of commutator, the V rings are tightened against the bars by means of a large nut that screws on the shell. The nut may be on either end of the commutator. Details of commutator construction are shown in Figures 5-92 through 5-98. Some commutators are tightened by means of large screws that extend from one ring to another. Still other types of commutators are riveted together and cannot be reinsulated.

When a commutator is disassembled, the holding nut is unscrewed, and the bars are tapped lightly with a hammer. This will cause the front V ring to come

off the shell; at the same time the bars will loosen and separate. Usually the mica segments will stick to the bars, and it will be necessary to loosen them with a knife. Small particles of mica may have to be scraped from the bars, although this may cause rough spots. If so, a medium grade of sandpaper is used to smooth the sides of the bars. One complete mica segment must be preserved so that its thickness can be measured with a micrometer. A segment of mica is usually from 0.020 to 0.040 in. thick. The mica comes in sheets about two feet wide by three feet long and is called *segment mica*. The mica end rings must also be saved so that they can be measured for thickness and used as templates for new mica rings.

Cutting New Mica Segments. After the thickness of the mica has been determined, cut the required number of segments by placing a commutator bar on a sheet of mica and marking off rectangular strips, as shown in Figure 5-99. This may also be done by measuring the length and width of one bar and then laying off these measurements on the sheet of mica. As a safety measure, it is best to make the dimensions about 1/32 in. more than the actual measurements. Next, cut off the strips with a paper cutter or shears.

To cut the Vs in the mica segments, proceed as shown in Figure 5-100. Place about six strips of mica between two bars, and place the combination in a vise, being careful to line up both bars so that they lie in similar positions. Use a hacksaw and cut out the mica along the dotted lines, as shown in the illustration. Do not let the hacksaw blade touch the bars because it will cut too deeply into the mica and at the same time weaken the bars. Reverse the position of the bars and micas in the vise and cut out the other half. Do not disturb the position of the bars and strips in turning them.

The hacksaw blade will leave a rough edge on the mica. Smooth this with a knife file while the bars and strips are still in the vise. The mica should be filed down to the same level as the Vs in the bars as shown in Figure 5-101; otherwise, the commutator will not tighten sufficiently. Remove the segments and bars, and place each mica segment face down on a piece of fine sandpaper and rub it lightly to remove any remaining rough edges. Repeat this process with the bars. This is just one method of cutting mica segments. Some mechanics cut one segment at a time with shears. The method depends on the individual.

Making New Mica V Rings. Besides making new mica segments, it may also be necessary to renew the mica V rings. The old rings may be used as a template for this purpose, or the iron V ring may be used.

In the first method, as much of the old mica ring as possible must be preserved. If the commutator has never been reinsulated, the ring will be in one piece. The V ring is actually two separate rings, an outer and an inner ring, that fit together as shown in Figure 5-102. To duplicate this ring, it is necessary to use a molding machine and press. Because this equipment is not usually available in the average repair shop, the outer and inner rings are made separately.

The method for making mica rings is as follows: Cut the original V ring along the line indicated in Figure 5-102, thereby separating the inner from the outer ring. Assume that the inner V ring is to be made. Cut the old ring, and then heat it over a gas flame or with a torch to soften it and prevent it from cracking. (Do not apply the flame directly to the mica.) The ring can then be laid flat and will assume a shape like that shown in Figure 5-103.

The flattened V ring is placed on a piece of molding mica, and several outlines of it are inscribed. These are then cut from the molding mica with a pair of shears. It may be necessary to apply heat to the mica during this operation to prevent it from peeling and cracking. (Molding mica that requires no heat is also available.) Heat the mica very gently and then mold with the fingers to fit the iron V ring. Make the thickness of the ring the same as the original. Several pieces of mica may have to be used to make up the required thickness. The same procedure is followed in making the outer ring.

A second method is to use the iron V ring as a template. Assuming that the outer mica ring is to be made, place a clean piece of paper over the ring and press on the paper, as shown in Figure 5-104, to form an outline whose dimensions will provide the size of the mica strip to be molded.

A third method uses a formula. Figure 5-105 shows that a cut-apart V ring is the top portion of a cone. A simple procedure in laying out a V ring is to find the size of the cone that will contain the ring.

Make a diagram like that in Figure 5-105, showing a cone with the shaded part representing the ring. If the cone is cut through, as indicated by the line, and rolled flat, a sector of a ring will be found. If the distances x and y are determined and the circles inscribed using these distances as radii, then the problem can be solved.

The procedure for finding these distances follows: Measure the distances A and B shown in Figure 5-106 on the iron V ring with a ruler. The cone can also be resolved into two triangles, R and S, which are alike except for size. A simple formula can be obtained from this relationship.

In two similar triangles,

$$\frac{a}{x} \text{ of triangle } R = \frac{b}{c} \text{ of triangle } S$$

or

$$\frac{a}{x} = \frac{b}{c} \text{ or } x = \frac{a \times c}{b}$$

Using the distance x as a radius, draw a circle. Lay out another circle inside this one using the distance y equal to $x - c$ as the radius. The ring formed by these two circles will represent the layout of the V ring.

Reassembling a Commutator. After the rings are made and the mica segments cut, the next step is to assemble the commutator. This is done in the following manner: Place the mica rings in position on the iron V ring and apply heat to mold them to fit. Put a bar in position on the V ring. Alongside the bar, place a mica segment, then a bar next to the segment, and so on. Make certain that there is a mica segment between every two bars. Be careful that the mica rings stay in position during the assembly. After all the bars and mica segments have been put together, place the top V ring in position and tighten the nut or through bolts. The tightening operation is performed while the commutator is being heated with a torch, Bunsen burner, or other source of heat.

The commutator must be tight and all bars aligned when the job is completed. If the bars are not in alignment, the commutator will have to be loosened and the bars twisted to the proper position. Some shops have clamps that are placed around the commutator while it is being tightened.

After the assembly, the commutator is given a ground and a short test. To determine whether the commutator is tight enough, tap the bars with a light hammer. A properly assembled commutator will produce a ringing sound, and a loose commutator will cause a hollow sound.

Shorted Bars. If there are shorted bars in a newly insulated commutator that has not yet been connected to the coils, it is a simple matter to reinsulate between the bars. However, if they are connected to the winding, it will be more difficult. When a shorted armature comes into the shop, determine whether or not the short is in the winding or in the commutator by lifting the leads from the suspected bars. These bars are then tested with test lamps to see whether they are shorted.

The usual procedure is to assume that there is a partial short due to carbonized mica or dirt between bars. To eliminate this possibility, grind down a hacksaw blade on the grindstone so that it has a hook end, as shown in Figure 5-107, and scrape away some of the mica. Sometimes it may be necessary to scrape rather deeply into the mica to remove the short. Carbonized mica is black and gritty, and good mica is white when scraped. Scrape the mica until the white mica can be seen. If this operation removes the short, then the hole that was made by the scraping must be plugged. This is accomplished by inserting a filler called *commutator cement,* which consists of powder made of pulverized mica and glue mixed to produce a paste. This filler is forced between the bars with a knife or blade and allowed to harden.

If a hole has been gouged in the mica, plug it with a new piece of mica and cover this with cement. This cement is a conductor while it is still wet and should not be disturbed until it dries thoroughly.

Reinsulating a Shorted Commutator While It Is Connected to the Winding. If the short cannot be eliminated by scraping the mica, remove several bars and put new mica segments in place. This is done in the following manner on a commutator that can be taken apart from the front end:

Unsolder the leads from the shorted bars. Unscrew the nut that holds the commutator together. Tap the bars lightly with a hammer to loosen the end ring and several bars. Remove the end ring and pull out the shorted bars with a pair of pliers, as shown in Figure 5-108. Use these bars to cut out a new mica segment. Replace the new mica and bars and reassemble.

If there is only one short and the commutator opens at the rear, an easy repair is to lift the leads from one bar and make sure they are soldered together and taped so that they cannot touch the commutator. Jump the two shorted bars. The circuit of this operation is shown in Figure 5-109. Another method consists of lifting the leads of the coil connected to the shorted bars and taping them individually. The shorted bars are jumped. This eliminates one coil from the winding. For other types of commutators, removal of the entire commutator from the shaft may be necessary.

Grounded Bars. Usually the ground takes place at the front mica ring. This occurs because part of the front ring is exposed, allowing oil, grit, or dirt to accumulate on it. The ground is easily detected, as usually a large hole will have developed, and part of the mica ring will have been burned away at the grounded spot. The best way to clear this is to remove the front ring, cut off the defective part of the mica ring, and replace it as indicated in Figure 5-110. New mica segments may have to be installed at the same time. Make sure that the mica pieces overlap one another to prevent the ground's recurring. If the commutator does not open at the front, it is removed by placing the armature in a mandrel or hydraulic press and pressed out. When it is impossible to remove the commutator without harming the winding, the old commutator is turned down completely in the lathe. Commutator measurements must be recorded beforehand so that a new commutator can be built. This is often done on smaller armatures. When the new commutator is constructed, it is desirable to put a cord band on the front mica ring and paint it with a good grade of insulating varnish or shellac. To a large extent, this will keep oil and dirt from penetrating under the bars and causing shorts and grounds.

High Bars. High bars, such as those shown in Figure 5-111, can be found by running the fingers over the bars. This condition is caused by loosening of the commutator due to excessive heat, shorted bars, poor assembly, and the like. To remedy this condition, tap the bar lightly with a hammer until it assumes the correct position, and then tighten the nut. Turn down the commutator in a lathe, or stone it if it is in a motor.

COMMUTATOR STONES. Commutator stones, made in various grades of coarseness, are used to smooth a rough commutator. The coarser grades are used on very rough commutators, and the finer grades for finishing purposes and on commutators that are not extremely rough. For high commutator bars, a medium grade should be used. While the armature is turning, the stone is held in the hand

and pressed against the commutator until a smooth surface is formed. Then a fine grade of sandpaper is held against the commutator to finish the job.

Low Bars. A low bar, as shown in Figure 5-112, is also recognized by running the fingers over the commutator. This condition may be caused by a blow from some heavy object. The remedy is the same as before: Turn down in a lathe, stone, and then sandpaper the commutator.

High Mica. If the mica segments are higher than the adjoining commutator bars, a condition called *high mica* exists. This condition may be caused by the commutator bars' wearing faster than the mica segments or by the use of improper carbon brushes. Where the mica is flush with the bars, a hard grade of brush should be used so that it will wear away the mica at the same rate as the bar.

The remedy for this condition is to undercut the mica so that it is below the surface of the bars. This operation can be performed by using a machine consisting of a small electric motor with a small saw wheel attached. While the armature is in a lathe, a cut is taken on each mica segment so that it is about 1/32 in. below the surface of the bar. The saw wheel must be the same thickness as the mica. Undercutting can also be done by utilizing a small file especially made for the purpose. Care must be taken to ensure that none of the mica is left on the sides of the bars, as shown at the right of Figure 5-113. If there is mica at the sides, it can easily be removed by cutting it away with a ground-down hacksaw blade. Figure 5-114 illustrates how a mica undercutter is used for a fractional-horsepower motor.

Chapter 6

DIRECT-CURRENT MOTORS

A dc motor is a machine that, when supplied with electric current, can be used for such mechanical work as driving pumps and running machine tools. Direct-current motors are also widely used in applications that require control of speed. Some of these are printing presses, electric trains, elevators, and drives. Direct-current motors are made in sizes varying from 1/100 hp to thousands of horsepower. A typical dc motor is shown in Figure 6-1.

CONSTRUCTION

The main parts of the dc motor are the armature, field poles and frame, end plates or brackets, and brush rigging. The armature is the rotating part of the motor and consists of a laminated steel core with slots in which coils of wire are placed. The core is pressed on a steel shaft that also holds the commutator. This latter conducts current from carbon brushes to the coils in the slots. Figure 6-2 shows an armature with straight slots, and Figure 6-3 shows skewed slots.

The frame of the dc motor is made of steel or cast iron, generally circular in form and machined so that the field pole can be mounted inside it, as shown in Figure 6-4. Many motors are also made with a laminated steel frame. The field pole is usually fastened inside the frame with screws or bolts, but on some small motors the field poles are part of the frame. On large motors, the poles are laminated as shown in Figure 6-5 and bolted to the frame. The field pole holds the field coils or windings, consisting of coils of insulated wire that are taped before being placed on the field pole.

Two end plates, fastened to the frame with bolts, bear the weight of the armature and keep it equidistant from the pole pieces (see Figure 6-6). The end plates contain the bearings in which the shaft of the armature revolves. These may be either sleeve bearings, as shown in Figures 6-7 and 6-8, or ball bearings, as shown in Figure 6-9.

On all dc motors, current must be conducted to the armature winding. This is accomplished by connecting leads from the winding to the commutator and, in

turn, feeding the commutator with current. The commutator can be supplied with current by allowing carbon brushes to ride on it and contact it while it is turning. The brushes are held in a stationary position by brush holders, which are generally mounted on the brush rigging shown in Figure 6-10. The rigging is usually mounted on the front plate and so constructed that the brush position may be changed. On small motors, the brush holders are usually cast as part of the plate. The brush holders on all motors are insulated from the end plate to prevent grounds and to prevent short-circuiting the brushes.

TYPES OF DC MOTORS

There are four types of dc motors: the permanent-magnet motor, the series motor, the shunt motor, and the compound motor. The main difference in these motors is in the construction of the field coils and in the connections between the field coils and the armature. The permanent-magnet motor has permanent magnet fields and an armature that is similar to any dc motor's armature. These motors are manufactured in fractional- to the low-integral horsepower sizes. In the smaller sizes, the control for speed and converting ac to dc is built into the motor's end bell.

The series motor contains field coils composed of a few turns of wire connected in series with the armature, as shown in Figure 6-11. This motor has a high starting torque and a variable-speed characteristic: the greater the load is, the lower the speed will be. The series motor is generally used in cranes, winches, trains, automobile starters, and the like. The shunt motor has wound fields like those of the series motor and a similar armature. The fields are wound with thousands of turns of fine wire. Both the fields and the armature are connected across the line (see Figure 6-12). This is a good motor for loads that need a steady speed, such as a fan. The compound motor has both a series field and a shunt field. The shunt field is connected across the line, and the series field is connected in series with the armature (see Figure 6-13a). This motor has good speed regulation, because of the shunt field, and good starting torque, because of the series field.

OPERATION OF DC MOTORS

The operation of dc electric motors can be explained with two magnets. If the like poles of two permanent magnets are held together and then released, they will fly apart. If like poles of two electromagnets are placed together and voltage is applied to them, they will fly apart. If the current is reversed in one of them, they will pull together. Figure 6-13b shows this being done.

The simplest dc motor has a wound armature and permanent magnet fields. Two permanent magnets are mounted in an iron shell so that one is north and one

is south with respect to the armature. The magnetic lines of force go from the north pole through the armature to the south pole and then return to the north pole through the iron shell. This shell is referred to as *back iron*. The armature is the electromagnet. The coils of the armature all are soldered to segments of the commutator. These segments act as a sliding switch, switching the current from the line to certain windings of the armature. The brushes, which are the other side of the sliding switch, carry the current from the line to the commutator segments. The brushes are stationary and positioned so that they will energize the coils of the armature in such a way that they create poles. But as the armature turns, the position of these poles in relation to the brushes does not change. The brushes are positioned so that the armature poles will repel the stationary field poles producing torque and rotation. To understand what happens as the speed of the armature increases, it is necessary to understand how voltage is generated in a dc generator.

GENERATING FACTORS

A dc generator and a dc motor are identical in structure and are interchangeable. Any dc motor can be used as a generator, and any dc generator can be used as a motor with only a minor change in the connections. The change in connections will be explained later. The following are factors that pertain to both.

When a conductor (wires of the armature) cuts the lines of force (magnetic field of the stator), a voltage is generated in that conductor (wires of the armature). There are three factors or rules that govern the amount of voltage generated:

1. The number of lines of force being cut.
2. The speed at which the conductors are cutting the lines of force.
3. The number of conductors cutting the lines of force.

When voltage is generated in an armature, the current flows in the opposite direction through the armature, as it would if the unit were being used as a motor. When a dc generator is added to a dc power line, the output voltage of the generator must be equal to the line voltage. If the generator cannot produce enough voltage, it will become a motor and use power instead of generating it, and the current will reverse in the armature. Likewise, if a motor is pulled faster than its adjusted speed, it will generate power. When this happens, the current in the armature will reverse and put power back on the line.

COUNTER ELECTROMOTIVE FORCE

As soon as there is rotation of the armature in a motor, the lines of force from the fields are cut by the windings of the armature, generating a voltage. This voltage

is the opposite polarity of line or applied voltage (the current flows in the opposite direction in the armature of a generator). The result of this is that the voltage generated is subtracted from the applied, or line, voltage. This voltage is called *counter* or *back electromotive force* (back e.m.f.). One volt of back e.m.f. cancels the effect of one volt of line or applied voltage. As the armature turns faster, more back e.m.f. or counter e.m.f. is generated. As more voltage or back e.m.f. is generated, the applied voltage becomes less effective. The applied voltage at the brushes does not change as the armature accelerates. Back e.m.f. occurs within the turns of the armature. Each turn in the armature generates a portion of the total back e.m.f. The turns near the center of the pole generate more than do those at the outer edges. The turns are in series with one another, and because of this, the voltage generated in each turn adds to the next in its ability to counter the applied voltage.

Counter e.m.f. can be compared to an automobile battery being charged. When the battery is low, the charging amps are high. This is because of the large difference between the charging voltage and the low battery voltage. As the battery becomes charged, the battery voltage goes up, becoming closer to that of the charger. When this happens, the current flow goes down. If the battery voltage equals that of the charger, no current will flow.

As back e.m.f. builds within the turns of the armature, less current will flow. Less current will produce less magnetism and less torque. The armature will reach a speed at which the generated back e.m.f. and the load will not let it go any faster. If the load is decreased, the motor will speed up slightly. This increase in speed will generate more back e.m.f. The increase in back e.m.f. will reduce the effect of the applied voltage, and the current will be reduced. The speed will again stabilize. There is not much difference between full-load rpms and no-load rpms. The voltage generated as back e.m.f. is always less than the applied voltage. Without back e.m.f., the current would be excessive in the armature circuit, and it would burn out.

When the applied voltage to the armature is reduced, the difference between the applied voltage and the back e.m.f. is smaller, and the armature will slow down. The amount of current in the armature will depend on the difference between the back e.m.f. and the applied voltage. As the armature slows down, fewer lines of force are cut and less back e.m.f. is generated. The speed will be reduced until the back e.m.f. allows enough current to flow in the armature to pull the load. The speed will then stabilize. There will be a decrease in the amperes in the armature at this lower speed because of less applied voltage.

When a controller lowers the voltage to the shunt field, the current flow in the shunt field will decrease. This will in turn decrease the lines of force. With fewer lines of force, there will be less back e.m.f. When the back e.m.f. is reduced, the applied voltage becomes more effective, and more current will flow in the armature. More current in the armature will result in an increase in speed. The speed will increase until enough back e.m.f. is generated to stabilize it. If the load is not reduced, more amperes will be flowing in the armature at this higher speed. The torque will remain the same, but the horsepower will be increased.

The speed of the permanent-magnet motor can now be explained. As the speed of the permanent-magnet motor increases, the lines of force from the permanent magnets are cut. This generates back e.m.f. in the armature. The top speed will be determined by the load, the back e.m.f., and the applied voltage. The speed of this type of motor is controlled by decreasing the applied voltage to the armature. The speed range can be full voltage, full-load speed, and below. The speed and the torque will vary with the voltage, and the amperes will be reduced with the speed.

If the permanent magnets become weak, there will be fewer lines of force for the armature to cut (Voltage Rule 1). With fewer lines of force to cut, the armature will not generate as much back e.m.f. at its loaded or designed rpms. The armature will speed up to generate the required back e.m.f. to stabilize the speed. If the load increases with the increase in speed, the amperes of the armature circuit will also increase. At this point, both the speed and the amperes are excessive, and so the armature will burn out. The permanent magnets can be remagnetized. Remagnetizing is necessary if a permanent-magnet motor speeds is 10 percent above its nameplate rating. There will be a loss of magnetism if the motor is reversed suddenly or stalled, or if the motor is disassembled without a magnetic ''keeper'' placed in the bore. This keeper can be any piece of iron that fits the bore with a minimum of air gap. This provides a path for the lines of force to go from pole to pole and keep the magnets from weakening.

Shunt Motor. Shunt motors have wound fields instead of permanent magnets (see Figure 6-12). These fields consist of thousands of feet of wire. When compared with the wire of the armature, the shunt-field wire is much finer. The shunt-field poles are connected across the line and can also have a voltage control connected in series to control the speed. With a voltage control, the number of lines of force from the poles can be varied. Full voltage applied to both the armature and the fields will produce the slowest speed at full load. When the control reduces the voltage applied to the fields, the current flow is then reduced. It is the current that produces the lines of force, and so the number of lines of force are also reduced. The number of lines of force (Rule 1) being cut are reduced, and so less back e.m.f. will be generated in the armature. This allows more current to flow in the armature, increasing its magnetic power, and so it will speed up. And more speed and current will increase the motor's horsepower. The armature is designed for this increase if kept within the nameplate limits. It may be noted that when considering the total amperes of a dc motor, a very small percentage of the operating amperes is needed to energize the shunt field. Most of the current flows through the armature. The shunt-field controller is called the *overspeed control* or *torque control*.

A controller can also be placed in series with the armature to control the voltage. Less-than-full voltage applied to the armature will decrease the motor's speed. The difference between the back e.m.f. and the voltage applied to the armature is smaller. The effect of the applied voltage to the armature also becomes smaller, and because of this, less current will flow through it, and the

torque will decrease. The load will slow the armature, and so fewer lines of force will be cut per second (Rule 2). With fewer lines of force being cut, the back e.m.f. decreases, allowing more current to flow in the armature and increasing the torque until the speed is again stabilized. This is called *underspeed* or *horsepower control*. The motor's ability to cool itself is reduced when running at a slower speed, and ventilation can become a factor if the motor is run slowly for a long time.

From no load to full load, the speed of a shunt motor will not change much, which means that the shunt motor has good speed regulation. Intermittent overloading, however, will slow the shunt motor considerably. There is a set amount of magnetic power in the shunt fields, which does not vary with the load and does not provide the extra power when an overload occurs. Because of this, the shunt motor does not work well with varying loads.

Series Motor. The field poles of a series motor are connected in series with the armature (see Figure 6-11). The current flow is the same throughout a series circuit, and so the current of the series field is controlled by the back e.m.f. of the armature. The series field has fewer turns of wire, and the wire is much larger than that of a shunt field. Because of the back e.m.f. limiting the current, the series field does not need as much resistance as the shunt field does.

As the speed of the series motor increases, the back e.m.f. also increases, but the current flow decreases. The current flows through the field poles so that the number of lines of force also decreases. When the lines of force decrease, so does the amount of back e.m.f. The back e.m.f. of a series motor is never enough to limit the speed; only the load can limit the speed of a series motor. In small motors, the friction of the bearings and the cooling fan load is enough to keep the speed at a safe level. Large motors cannot be run without a load because they will accelerate until the armature flies apart. This motor does not have good speed regulation, but it is popular for high-torque loads such as power tools, automobile starters, and traction motors for locomotives. This type of motor is small in size when compared with other types of motors of the same horsepower, and this makes them ideal for the above applications.

Compound Motor. The compound motor is constructed in much the same way as is the shunt motor, the difference being in the field poles. There is another winding wound on top of the shunt field called the series field. This winding has fewer turns and much larger wire than the shunt field does. It is connected like that of the shunt field, with adjacent poles having opposite polarity. Instead of being connected across the line as the shunt field is, it is connected in series with the armature, as the series motor is, as shown in Figure 6-13a. The shunt field gives this motor good speed regulation, as the shunt motor has, but the series field gives it the ability to handle overloads well. The current through the series field and armature increases when an overload decreases the speed of the armature. This increases the motor's power, and the overload does not reduce the

speed as drastically as it would with a shunt motor. The compound motor can be controlled for overspeed and underspeed in the same way that the shunt motor can.

Stabilized Shunt Motor. This motor is constructed in the same way as the compound motor is, except that there are only a few turns of wire in the series field. The number of lines of force provided by this winding is determined by the armature's current. As the motor is loaded, the lines of force are increased from the stabilizing field because of the increased current in the armature. This increases the back e.m.f., slowing the motor. The added lines of force, which will go up with the armature's current, increase the torque. The overall result of this winding's influence is less fluctuation in rpm from no load to full load, a reduction in the armature's current, and more torque at full load when compared with that of a shunt motor.

CONSTRUCTION OF THE FIELD COILS

Series field coils are wound with comparatively few turns of heavy wire whose diameter depends on the motor's amperes. The wire can be wound on a wooden form that consists of a centerpiece the size of the coil and two sidepieces to hold the coil in place. The construction of the form is given in Figure 6-14a. The centerpiece is usually slightly tapered to facilitate removal of the coil from the form. The proper shape of the coil is retained during its removal from the form if strips of tape or cord are placed on the centerpiece before the coil is wound. It can then be tied up easily after winding, as shown in Figure 6-15. The form is placed in a lathe chuck or coil-winding machine and wound with the same number of turns and the same size of wire as the original coil. The size of the form may be obtained from the original coil or by measuring the dimensions of the core and allowing for the thickness of the tape. Figure 6-16 shows a field after it has been taped with a layer of cellulose acetate film tape. Field coils can also be wound on a coil-winder head, as shown in Figure 6-14b.

Shunt fields consist of many turns of fine wire arranged as shown in the cutaway view of Figure 6-17. Inasmuch as there may be thousands of turns on a shunt-field coil, it is inadvisable to try to rewind this type of coil by counting the number of turns. The usual method is to weigh the old coil and to wind the new coil with the same weight and size of wire. The shunt coils are wound and taped in the same manner as are the series fields. Figure 6-17 also shows a finished coil.

The compound-field coil is a combination of a series field and a shunt field, as illustrated in Figure 6-18. The same type of form is used for the compound-field coils. First, the shunt-field portion is wound on the form. This must correspond to the original coil in every detail. To form the layer of insulation shown in Figure 6-19, several turns of acetate tape are placed around the coil while it is

still in the form, or the coil is removed and taped with acetate tape. In the latter case, the coil is replaced on the form after being taped. Next, the correct number of turns of wire for the series coil is wound. The cord on top of the insulation or tape is then tied, and flexible leads are soldered to the coil ends and taped. This is an important operation and must be done carefully. Usually the shunt-field leads are a smaller size of wire than are the series-field leads. The coil is taped with acetate tape and then with polyester film/polyester mat. The completed winding is shown in Figure 6-20. Figure 6-21 illustrates how a field coil is placed on the field core. On large motors, the series field is usually wound and taped separately and then placed alongside the finished shunt field. This type of construction is shown in Figure 6-22. On very large motors, to conserve space, rectangular wire is used on the series field.

An interpole field is used on many dc motors to prevent sparking at the brushes. This field is smaller than the main fields and is attached to the frame between them. Like the series field, it is wound on a form, usually fiber, with comparatively few turns of heavy wire. Figure 6-23 shows an interpole field and its core. The fiber form and coil are placed over the interpole core and fastened in position by wedges.

Caution. The shunt field must be properly insulated from the series field to prevent short circuits between fields.

While taping the field coil, tie down the flexible leads to prevent them from being ripped from the coils. The tape on the coil must not tear or rip while it is being placed on the core. Grounds may be caused by careless work.

Connecting Field Poles

In dc motors, the field coils are connected so that alternate polarity is formed. Thus, in the two-pole motor of Figure 6-24, one of the poles is north and the other is south; in a four-pole motor, the poles must alternate, as shown in Figure 6-25. The field poles are connected in series except on very large motors and on motors that have been reconnected from a higher to a lower voltage.

To form alternate polarity in the field coils, the current should flow through the first pole in a clockwise direction, through the second pole in a counterclockwise direction, through the third clockwise, and so on. It is extremely difficult to determine this direction if the fields are taped, and three methods may be used to obtain correct field coil polarity: (1) trial and error, (2) compass, (3) use of iron rod or nail.

The trial-and-error method should be used only on small two-pole motors. The field coils are connected as shown at *A* in Figure 6-26 and the motor assembled. If it does not rotate, reverse the two wires of one field coil, as shown at *B*, and the motor will run. This method assumes that the armature and field coils are in good condition. The shunt motor can be tested in the same manner.

The compass method may be used on any number of poles. If it is a compound motor, test one field winding at a time. For testing the field coils of a four-pole motor, the four fields are connected in series, as shown in Figure 6-27. Low-voltage direct current is applied to the fields if the series fields are being tested; otherwise, 115 volts can be used. A compass is placed near a pole on the inside of the motor or alongside the field coil, as shown in the illustration. A notation is made of which end of the needle points to the pole. When the compass is moved to the next pole, the other end of the needle should be attracted. If the same end of the needle is attracted, reverse the leads of this pole. This procedure is followed until all poles have been checked. The fields should alternate in polarity.

The procedure outlined above cannot be followed if the armature is in the motor. In this case, one end of a piece of soft iron is held against the field pole, with the other end extending outside the motor. To test for polarity, hold the compass against the outside end of the soft iron. Before it is touched to the next pole, the soft iron should be brought down sharply on the bench to disturb any residual magnetism which might tend to upset the compass needle. Continue in this manner until all poles are tested. As before, alternate polarity should be obtained.

A third method of testing polarity is to use an iron rod or nail. The field coils are connected in series and supplied with low-voltage direct current. The head of a nail is placed against one pole, as shown in Figure 6-28. If the polarities are correct, the other end of the nail will be attracted to the next pole; if incorrect, it will be repelled.

CONNECTING DC MOTORS

Series Motor

The series motor is connected as shown in Figure 6-29. This is a two-pole series motor. The fields are connected in series and then in series with the armature. Three diagrams clarify this.

Shunt Motor

The shunt motor is connected as shown in Figure 6-30. The shunt fields are connected in series for alternate polarity and across the line leads. The armature leads are also connected to the line so that the armature and the fields are in parallel.

Compound Motor

The compound motor is connected as shown in Figure 6-31. The shunt fields are connected in series for proper polarity and then across the line. The series fields are connected and tested for proper polarity. It is of the utmost importance that

the polarity of the series field corresponds to that of the shunt field on the same pole. A method that accurately determines this condition is described on page 199. The armature connection completes the procedure.

The motor shown in Figure 6-31 is one of four different types of compound motors. Although this connection is the one used most often and the one that should be used unless otherwise specified, it is essential to be familiar with the other types. The four types are *long-shunt cumulative, long-shunt differential, short-shunt cumulative,* and *short-shunt differential.*

In a long-shunt cumulative motor, the current flows through the series-field and shunt-field coils of a pole in the same direction, as indicated in Figure 6-32. Such a motor is said to be *cumulatively compounded.* When the shunt field is connected across the line, it is given the name of long shunt. The complete name of the motor is a long-shunt cumulative motor.

If the shunt-field connection of a compound motor is reversed with respect to the series field, the current will flow through it in the opposite direction, as shown in Figure 6-33. This produces bucking fields, and the motor is known as a *differentially connected motor.* Motors of this type are used infrequently and only on special work.

A *long-shunt differential motor* is one in which the shunt field is connected across the line so that the series and the shunt fields have opposite polarity in the same pole.

When the shunt field of a compound motor is connected to the armature terminals instead of across the line, the motor is known as a *short-shunt motor.* This motor can also be either cumulative or differential.

If the shunt field is connected across the armature so that the current flows through it in the same direction as the series field, the motor is known as a *short-shunt cumulative motor.* This type is shown in Figure 6-34.

If the shunt field is connected to the armature so that the current flows through it in the opposite direction to the current in the series field, the motor is known as a *short-shunt differential.* This type is shown in Figure 6-35.

Interpoles

Nearly all shunt and compound motors of one-half horsepower or more have commutating poles or interpoles located between the main poles. These interpoles have one winding of heavy wire and are connected in series with the armature, as shown in Figure 6-36. The purpose of the interpole is to prevent sparking.

There are usually as many interpoles as main poles, although half as many may be used without causing inefficient operation. Although the interpoles are connected for alternate polarity, just as the main poles are, they also have a definite polarity with respect to the main poles. The polarity of the interpoles depends on the polarity of the main poles and the direction of the motor's rotation.

Rule for Interpole Polarity. The polarity of an interpole in a motor is the same as the main pole behind it. This means that if a motor viewed from the commutator end is rotating clockwise, the polarity of the interpole must be the same as that of the main pole that precedes it in the direction opposite to rotation. Figures 6-37 to 6-39 show two- and four-pole interpole motors connected for counterclockwise and clockwise rotation.

Figure 6-40 shows a schematic diagram of a compound-interpole motor.

A two-pole, compound-interpole motor connected for counterclockwise rotation is shown in Figure 6-41. The procedure for connecting this motor is as follows: Connect the shunt-field coils in series for proper polarity and bring the two lead wires out of the motor. Note the polarity of one pole. Perform the same operation for the series-field coils, and bring two wires out. Connect the interpoles in series for alternate polarity; then connect them in series with the armature, bringing out one interpole lead and one armature lead. Six leads have been brought out of the motor, two shunt-field leads, two series-field leads, and two armature-interpole leads. (Sometimes one shunt-field and one series-field wire are connected together inside the motor and one lead from the two brought out, making a total of five out of the motor.) Connect the six leads as shown in Figure 6-41 so that a compound motor results.

Because the motor is to be connected for counterclockwise rotation, the interpole polarity should be the same as that of the main pole behind it. Therefore, in testing the interpoles for polarity, make sure that not only is alternate polarity formed but also that the polarity is correct with respect to the main pole. This is the reason for noting the polarity of one main field.

If the motor runs in a clockwise direction, it will be necessary to reverse the direction of rotation. This is done by reversing both the armature and the interpole as a unit in Figure 6-42. The polarities of all the fields remain the same. See page 205, "Test for Correct Interpole Polarity."

REVERSING DC MOTORS

Direct-current motors are reversed by changing the direction of current flow through the armature or through the field. In series motors, the usual procedure is to reverse the current through the armature. Figure 6-43 shows this method. All that is necessary is to interchange the leads on the brush holders. Figure 6-44 shows the series motor reversed by changing the current in the field circuit. In this case the field leads are interchanged.

A shunt motor has the direction of rotation changed in the same manner as a series motor does. Figure 6-45 shows a two-pole shunt motor that is reversed by interchanging the armature leads. To reverse a shunt-interpole motor, it is necessary to reverse the current flow through both the armature and the interpoles as a unit. This method is shown in Figure 6-46. Reversing the armature leads without the interpole will cause the motor to have incorrect interpole polarity, which will make the motor run excessively hot and will produce sparking at the brushes.

Reversing a Two-Pole, Compound-Interpole Motor. Figure 6-47 shows a two-pole, compound-interpole motor with six leads brought out of the motor. The interpoles are connected in series with the armature, and two wires, A_1 and A_2, are brought out from this as a unit. In the diagram, the armature is connected between the interpoles. (The interpoles are sometimes connected in series and then connected to the armature.) To reverse this motor, it is necessary to reverse the interpole and armature circuit as a unit. Wires A_1 and A_2 must be reversed, as indicated in Figure 6-48.

Reversing a Four-Pole, Compound-Interpole Motor. A four-pole compound-interpole motor is reversed in the same manner as a two-pole motor is. Figure 6-49 shows a four-pole motor that is reversed by interchanging leads A_1 and A_2.

Caution. If the leads at the brush holder are reversed, the brushes will spark, and the armature will overheat. Under these conditions, the motor will not operate properly. On all interpole motors, the armature circuit (armature and interpole) must be reversed as a unit for opposite rotation.

TROUBLESHOOTING AND REPAIR

Testing

A new dc motor should be tested before it is installed, and the same tests can be performed when the condition of a motor on the job is being determined and when a repaired motor is being given a final check. Proceed as follows:

1. Test for grounds in the fields, armature, and brush holders.
2. Test for opens in the field circuit and in the armature circuit.
3. Test to identify the six leads of a compound motor.
4. Test for cumulative or differential connection.
5. Test for correct interpole polarity.
6. Test for correct position of the brush holders.

1. Ground Test. Before a motor can be given a ground test, all external leads must be disconnected from it. This applies especially to a motor that is being tested on the job. The following procedure applies to a compound motor, but any type of dc motor is tested in the same manner: Use a test set with a lamp and place one test lead on the frame of the motor; with the other test lead touch each motor lead in succession, as shown in Figure 6-50. The test lamp should not light. If it does, a ground is indicated. Determine whether the ground is in the field circuit (the shunt or series field) or in the armature circuit.

If a ground is indicated on the series fields, the interpole, or the shunt fields, it will be necessary to remove the fields from the frame and reinsulate them with tape. Figure 6-51 shows positions where grounds are most likely to occur. A

grounded field coil may be burned and several wires broken, necessitating rewinding of the field. A grounded field circuit does not mean that all the field coils are grounded; usually only one is defective. To locate the defective coil, the connections between coils are broken, and each pole is tested alone, as shown in Figure 6-52a.

Motors that are permanently installed are required by the Electrical Code regulations to have the frame grounded to a pipeline that connects to the earth. This is a safety measure in case the windings ground. If the frame is not grounded, the operator may receive a serious shock when touching the motor. With the frame grounded, a fuse will burn out and indicate that something is wrong with the motor.

A grounded coil can also be found by applying limited dc current from a test panel to one of the leads of the grounded winding and the frame of the motor, as shown in Figures 6-52b and 6-52c. The coils between the lead and the ground will produce magnetism and attract a screwdriver blade, as shown. The coils beyond the ground will have no current through them and so will not attract a screwdriver blade. Next apply the limited dc to the other winding lead and the motor frame, and check for magnetism. The lead nearest the grounded coil will have the highest amp reading. Only the coils between the lead energized and the ground will have magnetism.

A field coil will sometimes become grounded because it is loose on the pole shoe. A small amount of vibration will cause the metal of the pole shoe to wear through the insulation.

*2. **Test for Opens**.* Different tests are used for the series, shunt, and compound motors.

OPEN CIRCUITS IN A SERIES MOTOR. On small series motors, only two wires are brought out of the motor for connection to the line. The field and armature connections are made internally. If the two wires are connected to the test leads, as shown in Figure 6-53, the lamp should light and indicate a complete circuit. If the lamp does not light, the trouble may be caused by (1) the brushes' not making contact with the commutator, (2) a broken wire in the field, (3) a broken connection between fields, or (4) a wire disconnected or broken on the brush holder. The same test may be used on large series motors with external leads to field and armature.

OPEN CIRCUITS IN A SHUNT MOTOR. There are two circuits in a shunt motor, one through the shunt field and one through the armature. On small motors the connections are made internally, and only two wires are brought out. Therefore, to test such a motor for opens, it must be disassembled in order to reach the field and armature wires.

If the wires are accessible, as indicated in Figure 6-54, test each circuit separately. The lamp should light brightly when the armature circuit is tested. The

shunt field should produce a dim light. If it is not known which of the four wires is the shunt field and which is the armature, they can be determined by this test. If the armature circuit shows an open, the trouble may be the brushes, the connections to the brushes, or the armature windings; if the field tests open, then the trouble is either the field coil or its connections.

Open Circuits in a Compound Motor. For testing purposes, the compound motor is considered as having three circuits, one through the shunt field, one through the series field, and one through the armature. Figure 6-55 shows six leads brought out of a compound motor, two from the shunt field, two from the series field, and two from the armature. If the armature leads are tested with the test lamp, the lamp should light, indicating a complete circuit. The same holds true for the series-field circuit and the shunt-field circuit. Thus, three complete circuits are formed. If the open is in the armature circuit, the trouble is in the brushes or connections to the brushes or the interpole. If the trouble is in the series or shunt field, test for a complete circuit from one coil to another, as shown in Figure 6-56.

The following procedure is used to locate an open field coil on the four-pole motor, as illustrated in Figure 6-56. This method can be applied to a motor with any number of poles. Remove the insulation on the connections between the field coils, and connect a test wire to one field lead. Move the other test wire successively from one connection to the next until the lamp lights. In Figure 6-56, for example, move the test lead from *1* to *2*, to *3*, and so on, until the lamp lights or a spark is obtained. If the lamp lights or the test lead sparks at point *2*, then coil *1* is open; if the lamp lights at point *3*, then coil *2* is defective, and so on.

3. Test to Identify the Six Leads of a Compound Motor. The leads of a compound motor are always marked before it is shipped from the factory. Typical markings are shown in Figure 6-57. The armature leads are marked A_1 and A_2, the shunt-field leads F_1 and F_2, and the series-field leads S_1 and S_2. If the lead markings have disappeared, it is necessary to test the six leads for remarking before the motor can be properly connected. They can be identified in the following manner:

Use the test lamps, as shown in Figure 6-58, to determine the three circuits of the armature, the series field, and the shunt field. Three pairs of leads are obtained from the procedure. One pair of leads will cause the test lamp to light dimly. These connect to the shunt field. Both of the remaining pairs will cause the lamp to light brightly.

Remove the carbon brushes, and the lamp will not light when applied to one pair. These leads connect to the armature. The remaining pair are the series-field leads. This procedure is illustrated in Figure 6-58.

This is but one way of identifying the leads. There are many other methods: For example, the motor may be taken apart and the leads traced. This *must* be done on a five-lead compound motor. Sometimes the shunt-field leads can be immediately identified by the fact that they have a thinner lead wire than the

others do. The armature wires can occasionally be traced directly to the brush holder, thus eliminating this circuit. Common sense and a knowledge of circuits are essential to this kind of testing.

4. Test for Cumulative or Differential Connection. Compound motors are almost always connected for cumulative operation. This connection is sometimes impossible to determine unless the motor is tested when it is disconnected from the load. Test in the following manner: Connect the leads to produce a compound motor, as shown in Figure 6-59, and operate it from a dc source. Note the direction of rotation. Stop the motor and disconnect one shunt-field lead, thereby changing it to a series motor. Run the motor for an instant and note the direction of rotation. If the direction of rotation is the same in both cases, the motor is cumulatively connected. If it runs in the opposite direction after the shunt field is disconnected, it is connected differentially. If it is desired to connect it cumulatively and this test proves it to be connected differentially, reverse either the shunt-field leads or the series-field leads. Quite often this test is performed by connecting the leads to produce a compound motor, as described above, and shorting out the series fields before running it to note the direction of rotation. This is done to avoid an error in case of a large inrush of current. The rest of the test is as explained above, except that the short is removed from the series field.

5. Test for Correct Interpole Polarity. The compass cannot often be used in checking the interpoles on a job, especially if the armature cannot be removed from the motor. The following method may be used on motors in which the brush holder can be shifted from one position to another. No compass is needed, nor is it necessary to remove the armature from the motor.

Connect the line leads to the armature and interpole circuit. Disconnect all other wires. Mark the positions of the brushes and shift the brush holder so that the brushes are halfway between the marks. This is shown in Figures 6-60 and 6-61. Turn on the current for an instant and note the direction of the armature's rotation. If the armature turns in the same direction as the brushes are shifted, the polarity of the interpoles is right. If it rotates in the opposite direction, the polarity is wrong, and the interpole connections must be reversed. To make this test, the brushes can be shifted either clockwise or counterclockwise. After the test has been made, shift the brushes back to their original position. The shunt-field leads are then connected and the motor operated as a shunt-interpole motor for the direction in which the motor is to run. If the motor rotates in the proper direction, disconnect the shunt field and connect the series field in the circuit so that it runs as a series-interpole motor in the same direction as before. A low voltage must be applied. Now reconnect the shunt field. Remember that the interpole and armature as a unit are used for reversing purposes.

6. Test for Correct Position of Brush Holder. The number of carbon brushes riding on the commutator depends on the number of poles in the motor. A two-pole motor has two brushes; a four-pole motor has four brushes; and so forth. These brushes must be equally spaced around the commutator and must be

located in the correct position. Each brush must contact at least two bars at a time. In doing so, the brush short-circuits the coil connected to these bars.

If an armature coil cuts magnetic lines of force, current will be induced into the coil. If this coil is shorted by the brushes, the induced current will burn it out or produce considerable sparking. There is one place on a motor where the coil will cut comparatively few lines of force, and this point is between the main field poles. If a coil is shorted by the brushes when it is at this point, the coil cannot burn out because current is not being induced into it. Therefore, the brushes must be placed in such a position as to short-circuit an armature coil while it is midway between poles or at this neutral point.

To locate the brushes properly, proceed as follows: Assume a two-pole interpole motor, although the method applies to motors having any number of poles. The entire procedure takes place while the motor is assembled. Mark one armature coil slot with chalk and trace its leads to the commutator. Turn the armature in the motor so that the marked slot is under the interpole. With the armature held in this position, move the brush holder so that one brush is over the commutator bars connected to the coil. Fix the brush holder in this position.

Run the motor for a short time with the brushes in this position. Then shift the brushes back and forth very slowly and notice whether the motor runs more quietly or without any sparking. The location of the brushes one bar away from the determined position may cause better operation; if so, leave the brushes in the new position. Practice and experience will enable the repairperson to locate the exact position.

A popular method of determining the proper brush position consists in spacing the leads of a low-reading voltmeter to contact adjacent commutator bars. The motor is operated, and the leads are moved back and forth until no reading is visible on the voltmeter. This position is the correct neutral point. The brush holder is then moved so that a brush is in this position.

Several more ways to set brushes on neutral are:

1. To put normal current in the armature and interpole circuit without any field current. When the brushes are in neutral, the armature will not turn.
2. To use a field kick; that is, put a voltmeter across the brushes; then apply current to the field only, and note the kick on the voltmeter. In neutral position the kick will be zero or minimum.
3. To run the motor (loaded) in both directions; in neutral position the speeds should be identical.

Repairs

The symptoms encountered in defective dc motors are given below. Under each symptom are listed the possible troubles. The numbers in parentheses after each trouble indicate the correspondingly numbered remedies to be found in the following pages.

1. If the motor fails to run when the switch is turned on, the trouble may be
   a. Open fuse or protective device (1).
   b. Dirty or clogged brushes (2).
   c. Open armature circuit (3).
   d. Open field circuit (4).
   e. Shorted or grounded field (5).
   f. Shorted armature or commutator (6).
   g. Worn bearings (7).
   h. Grounded brush holder (8).
   i. Overload (9).
   j. Defective controller (10).
2. If the motor runs slowly, the trouble may be
   a. Shorted armature or commutator (6).
   b. Worn bearings (7).
   c. Open armature coils (11).
   d. Brushes set off-neutral (12).
   e. Overload (9).
   f. Wrong voltage (13).
3. If the motor runs faster than nameplate speed, the trouble may be
   a. Open shunt-field circuit (14).
   b. Series motor running without a load (15).
   c. Shorted or grounded field (5).
   d. Differential connection in a compound motor (16).
4. If the motor sparks, the trouble may be
   a. Poor brush contact on the commutator (17).
   b. Dirty commutator (17).
   c. Open circuit in the armature (3), (11).
   d. Wrong interpole polarity (19).
   e. Shorted or grounded field (5).
   f. Reversed armature leads (22).
   g. Wrong lead swing (18).
   h. Brushes set off-neutral (12), (18).
   i. Open field circuit (4).
   j. High or low bars (20).
   k. High mica (21).
   l. Unbalanced armature (24).
5. If the motor is noisy in operation, the trouble may be
   a. Worn bearings (7).
   b. High or low bars (20).
   c. Rough commutator (17).
   d. Unbalanced armature (24).
6. If the motor runs hot, the trouble may be
   a. Overload (9).
   b. Sparking (17), (11), and Section 4 above.
   c. Tight bearings (23).
   d. Shorted coils (5), (6).
   e. Too much brush pressure.

1. Open Fuse or Protective Device. Tests for a burned-out fuse have been described in previous chapters. The following notes will also be of value.

Some types of cartridge fuse can be taken apart and a new fuse wire inserted. Plug fuses are constructed so that by looking at the mica window it can be easily determined whether or not the fuse is good. The fuses can be tested without removing them from their cutouts. This is done by first connecting a lamp across the line before the current goes through the fuses. Next the test lamp is brought to the other side of the fuses; if no light is obtained, one or both fuses are blown. Breakers can be snapped back into the on position. Overload protectors on starters can be reset.

2. Dirty or Stuck Brushes. Carbon brushes should press against the commutator with a pressure usually between 1 and 2 lb. per sq. in. of surface. This pressure is applied by means of a spring, which is generally located behind the brush. For the spring action to be effective, the brush must be free to move in the brush holder. However, there must be as little space as possible between the brush and the brush holder. If too much room is allowed, the brushes will chatter while the armature is turning.

If the brush becomes so jammed in its mounting as to render the spring useless, the brush will not press on the commutator. Current will therefore be kept from flowing through the commutator and the winding and will produce, in effect, an open in the armature circuit.

The brush holders should be no more than 1/16 in. above the commutator; otherwise the brushes will chatter while the armature is turning. Figure 6-62 shows various positions of a brush. The proper distance can usually be regulated by means of a setscrew. It is also important that the brushes fit the curvature of the commutator. This is done by placing a strip of sandpaper over the commutator with the rough side against the brush and moving the sandpaper back and forth while pressure is applied to the brush.

3. Open Armature Circuit. An open armature circuit may result from numerous causes, such as (a) poor brush contact, (b) a broken wire leading to the brush holder, (c) a defective connection between the interpole and the armature, (d) a broken interpole wire, (e) two or more open coils in the armature, or (f) a dirty commutator. These faults are located either by visual inspection or by means of test lamps. Some of these troubles are illustrated in Figure 6-63. If there are open coils in the armature, repair by rewinding or by bridging commutator bars.

A dirty commutator should be cleaned with a dry cloth and then sandpapered. If the commutator is undercut, the dirt between the bars should be scraped out with hacksaw blades ground to fit into the slot.

4. Open Field Circuit. Open circuits in the series fields will prevent the motor from starting. If a shunt-field coil opens while the motor is running, it may cause the motor to "run away" if the motor is not fully loaded. On compound fields,

there is often a short circuit between the series and the shunt coils, causing the wires to burn and open-circuit. Figure 6-64 shows several places where opens may occur. Sometimes the opens take place in the leads connecting to the fields. These leads are broken off easily if they are not tied securely to the coil. The open may also be in the lead extending out of the motor or be due to a poor connection of the field poles. It is located either by inspection or by testing.

To repair an open field, remove it from the core and unwind or cut away the tape covering. If the break is on the top layer of the coil, remove the few turns and then attach the lead to this point. A few turns less on the coil will have no harmful effect on the operation of the motor. If many turns must be removed, splice new wire at the break and add the same number of turns to the coil as are removed. Occasionally the break may be one in which the two ends of the wire can be spliced without removing any turns. If the break cannot be located, rewind the entire coil.

5. Shorted or Grounded Field. A shorted field coil will either cause a fuse to burn out or produce a weak magnetic field that will not turn the armature. A completely burned field can be found by visual inspection, but a shorted field can be detected only by testing. Often a shorted field may cause the motor to run faster than normal and spark badly if no load is applied.

Three ways to test for a shorted field are (a) resistance measurement test with an ohmmeter, (b) drop-in-voltage test, and (c) transformer test.

RESISTANCE MEASUREMENT TEST WITH AN OHMMETER. Because all field coils in a given motor are alike, the resistance should be the same for each. Figure 6-65 shows the test circuit. The resistance of each coil is checked with an ohmmeter, and if the reading is lower on one field than on the other, a short is indicated. The shorted coil must be rewound.

DROP-IN-VOLTAGE TEST. If the field coils of a four-pole motor are connected in series to a 120-volt line, each coil will receive one-fourth of 120 volts, or 30 volts. Therefore, if the voltage across each coil is measured with a voltmeter, as shown in Figure 6-66, the reading should be 30 volts. The usual method of expressing this is to say that there is a 30-volt drop across the coil. If one field coil has a lower voltage drop than the others, a short is indicated.

TRANSFORMER TEST. Small field coils are tested as shown in Figure 6-67. The transformer consists of a laminated iron core with a coil around one end. The field coil is placed over the iron core so that it rests on the transformer coil, and 115 volts of alternating current is applied to the transformer. If the field coil is shorted, current will be induced into it and cause it to be repelled from the transformer coil. The field coil will jump upward if many turns are shorted.

Another method of detecting a shorted field coil is to connect the field-coil circuit to the line for a few minutes. Normally, all the field coils should become warm; if a coil feels cool, it is the shorted one.

One grounded coil will have no effect on the performance of a motor other than to cause a shock if touched. Two separate grounds in the motor are equivalent to a short and may cause a fuse to burn out. If the frame of the motor is grounded according to the Electrical Code, one grounded field may blow a fuse. Repair of a grounded coil involves reinsulating and retaping the grounded part. Care must be exercised in this operation, as some of the turns may have become open or badly burned. Be sure to examine carefully the grounded area.

6. Shorted Armature or Commutator. If there are many shorted coils in an armature or if more than one coil is grounded, the armature may not rotate. In some motors, the armature will revolve a half-turn or turn over very slowly. To test for shorted coils, place the armature on the growler and test with a hacksaw blade. Before doing so, however, clean the mica between the bars of the commutator to eliminate this as the possible cause of the shorts.

A shorted armature coil manifests itself by heating and smoking. Smoke issuing from a motor is nearly always a sign of shorted or burned coils. Sometimes the smoke is pronounced, but at other times it is hardly noticeable. The odor of burning coils is quite evident. If this condition is allowed to exist for a short time, the adjacent coils will be harmed. On the other hand, if it is caught in time, the winding may be saved. Whenever smoke is seen issuing from a motor, turn off the current and then locate the defective coil by feeling the armature for the hot coil. Cut it out of the circuit, as explained in Chapter 5.

If the shorted coil is due to shorted bars, lift the wires from *one* of these bars, solder the wires together, and tape them. Next solder across the top of the shorted bars. If the motor runs without smoking, the coil need not be cut through. If the coil smokes, this will be necessary. Shorted bars can nearly always be identified by discoloration due to the heat.

7. Worn Bearings. If the bearings are so worn that the armature rests on the field poles, the armature probably will not rotate. If it does, it will be noisy in operation. Try to move the armature shaft up and down to detect this condition, as explained in Chapter 1. Worn bearings are easily recognized by the noise produced and by the presence of smooth worn spots on the rotor core. The only remedy is to install new bearings.

8. Grounded Brush Holder. One grounded brush holder may cause the fuse to burn out if the frame is grounded. This is especially true if the motor operates on 230 volts. Use a test-lamp set to test for grounded brush holders. All wires must be disconnected from the brush holder and the brushes lifted from the commutator before this test is made. One test lead is held on the end plate while the other is touched to each brush holder in turn. A light indicates a grounded brush holder. To remedy, remove the brush holder from the brush rigging and reinsulate with fiber washers or mica at the grounded spot.

9. Overload. If an excessive load is placed on a motor, it may not turn over. A very hot motor is a sign of overload. To determine whether a motor is overheated, disconnect the belt or other connecting mechanism and try the motor. If it operates perfectly, in all probability the trouble lies in the load. Either decrease the load or install a larger motor. See Chapter 3 for a detailed description of this fault.

Overload does not necessarily refer to the actual load. Any condition that will cause the motor to run slowly is a form of overload; for example, tight bearings will tend to slow down a motor and are considered an overload.

Check the current flow through the motor with an ammeter and compare the reading with the nameplate current. If it is due to a heavy load, use a larger motor or cut down the load. The overload may be due to defective windings, for example, shorts, opens, or grounds. An ammeter or snap-around ammeter will read higher than normal; this obviously indicates trouble in the motor if external sources have been eliminated. In this case, the motor must be dismantled to determine the malfunctioning part.

10. Defective Controller. A controller that does not function properly may be the sole cause of burned-out fuses. The fault may lie in defective controller circuitry or in faulty connections between the motor and the controller. In either case, the repairperson should be familiar with controller operation and connections before attempting to make repairs. See Chapter 7, Direct-Current Controllers.

11. Open Armature Coils. An open armature coil will cause vicious sparking at the commutator and will prevent the motor from running at nameplate speed. Examination will reveal badly burned spots on the commutator bars to which the open coil is connected. On a lap winding, one open coil will cause one burned spot; on a four-pole wave winding, two spots will be produced. The open circuit may be caused by loose leads in the commutator bars or by improperly soldered leads. Remove the leads from the bar, clean them, and then replace and resolder them. If the open is caused by a broken wire in the coil, jump the two bars on either side of the burned spot. When more than one burned spot appears on the commutator, jump the bars in only one place and run the motor. If the sparking is eliminated, do not jump any more bars.

12. Brushes Set Off-Neutral. The brushes must short-circuit a coil while it is in a neutral zone. If the setscrew that holds the brush rigging in place becomes loose, it may cause the brushes to move away from the proper brush setting. When this happens, the armature will spark badly and cause the motor to lose speed. Place the brushes in the proper position.

This condition is similar to having a wrong lead swing. The remedy for it is to shift the brushes so that there is no sparking when the motor is running at full load. The correct position of the brushes in an interpole motor can be found by

turning the armature so that one coil lies midway between main poles or directly under an interpole, as shown in Figure 6-68. Next, the leads of that coil are traced to the commutator, and then the brushes shifted so that the commutator bars are shorted. The voltmeter method can also be used. In a motor that has no interpoles, the brush position, determined by the direction of rotation of the motor, will be slightly different. If the motor is running clockwise, the brushes must be moved counterclockwise several bars from the position they would occupy if it were an interpole motor.

13. Wrong Voltage. Motors are designed to run at a specific voltage. If the impressed voltage is less than the nameplate requirement, the motor will run at a correspondingly lower speed. If a load is applied, the motor will undoubtedly refuse to turn and may even burn out a fuse. Be certain that the nameplate voltage corresponds to the impressed voltage.

If in doubt as to the value of the line voltage, measure it with a voltmeter.

14. Open Shunt-Field Circuit. If the field circuit of a shunt motor opens while the motor is running without a load, the armature may rotate at such a high speed that there is danger of the coils' flying out of the armature. The motor is said to be "running away" if a condition like this arises.

15. Series Motor Running without Load. The load should never be removed from a series motor while it is running. If it is removed, the speed of the motor will increase until it is dangerously high. Figure 6-69 shows that the same amount of current flows through the fields as through the armature. Because a motor consumes more current when pulling a load than when running without a load, the strength of the field in a series motor will be low when there is no load and high when there is a heavy load. To generate the required counter e.m.f. with a weakened field, the armature must turn correspondingly faster.

16. Differential Connection in a Compound Motor. If a cumulatively connected motor is connected differentially by mistake, the motor will run at a higher speed if it is not loaded. Inasmuch as differentially connected fields have polarities that oppose each other, the resultant field strength will be weak. Previous discussion has shown that a weakened field causes an increase in speed.

Differentially connected fields are detected by observing the direction of rotation with the motor connected first as a compound motor and then as a series motor. If the direction is the same with both connections, it is connected cumulatively; otherwise, it is connected differentially. To change a differentially connected motor to a cumulative connection, the polarities of either the series or the shunt field are reversed.

17. Poor Brush Contact on the Commutator. Sparking at the commutator is a common occurrence, and one of the chief causes is poor brush contact on the

commutator. This may be due to (a) worn brushes; (b) clogged brush holder; (c) insufficient spring pressure; (d) loose pigtail connection; (e) brushes shaped improperly; (f) a rough, grooved, or eccentric commutator; or (g) dirty commutator.

Continual service will cause a brush to wear to such an extent that the spring pressure is no longer effective. This condition is illustrated in Figure 6-70. Vicious sparking will result. Replace with new brushes. Quite often the heat produced at the brushes will cause the spring to lose its tension. Inspection of the spring will reveal this fault; a defective spring can be stretched without returning to its original position.

If dirt and grease become lodged between the sides of the brush and the brush holder, the brush cannot press tightly against the commutator, and sparking results.

Many brushes are equipped with pigtails, as shown in Figure 6-71. These are small flexible leads that connect to the brush holder and conduct current from the brush holder to the brush. (In nonpigtail brushes this is done by means of the spring.) If the pigtail connections become loose, sparking will result. To tighten a pigtail in the brush, drop a piece of molten solder into the space between the pigtail and the brush with a soldering iron.

Failure to fit a brush properly against the commutator will also result in sparking. The brush is shaped by placing a piece of fine sandpaper on the commutator with the rough side facing the brush and moving the sandpaper back and forth while pressure is placed on the brush. After it has assumed the shape of the commutator, remove the sandpaper and blow away the carbon particles.

A rough and eccentric commutator will cause a distinct knocking and may be detected by placing a finger on it. The remedy is to turn down the commutator in a lathe. A dirty commutator is another cause of sparking. The commutator must be clean and free from foreign matter such as grease, oil, grit, and so on. The best way to clean a commutator is to wipe it off with a cloth. On undercut commutators, scrape out the dirt between the bars. Very often, small particles of carbon dust lodge in the mica between bars and flash over while the armature is turning. This may become so bad that a ring of fire forms around the entire commutator. Cleaning the mica will remedy the condition.

18. Wrong Lead Swing. If the coil leads of an armature are incorrectly placed several bars away from the right ones, excessive sparking will occur at the brushes. An examination of a coil in a neutral position will reveal whether or not its leads are being shorted by a brush. If the bars of this coil are not being so shorted, the leads obviously were put in the wrong bars. The remedy is to shift the brushes until no sparking results or to reconnect the leads if the motor brushes cannot be moved.

19. Wrong Interpole Polarity. The purpose of the interpole is to prevent sparking that results from induction; however, this can be accomplished only if the

polarity of the interpole is correct. Because the reasons for sparking are so numerous, it is difficult to examine a motor that is sparking and conclude that the cause is wrong interpole polarity. Testing is the only method of determining conclusively that incorrect interpole polarity is responsible. The test for correct polarity, which involves shifting of the brushes and noting the direction of rotation, was described earlier in this chapter. If the motor is so constructed that this test cannot be applied, a compass polarity test will have to be made.

A motor with wrong interpole connections will draw more than the normal current, and it thus will overheat. If the motor is allowed to run, the commutator will become so hot that solder will be thrown from the commutator slots. Even though the interpoles are not connected properly, the motor will often run without sparking, but the commutator will become abnormally hot.

20. High or Low Bars. High or low bars will cause excessive sparking at the commutator. If the motor turns slowly, a spark is seen every time the high bar passes the brush. If the motor turns rapidly, this condition will appear as a continuous spark, accompanied by a blackening of the commutator and by chattering of the brushes. High and low bars can be found by running a finger over the commutator. Tighten the commutator and turn it down in the lathe or use a commutator stone and sandpaper.

21. High Mica. High mica may be due to a loose commutator or, more usually, to faster wear of the copper bar than of the mica. Pronounced sparking accompanies this condition. High mica is recognized by a blackening of the entire commutator, and the mica will feel rough to the touch and higher than the bars. The remedy is to turn the bars down on a lathe and undercut the mica. A temporary repair is to hold a commutator stone against the bars while the motor is turning.

22. Reversed Armature Leads. This defect can occur only in a rewound armature and is manifested by sparking at the brushes. If everything else appears to be in good condition, the only way definitely to determine reversed leads is to retest the armature. A description of testing for reversed armature leads is given in Chapter 5.

23. Tight Bearings. If the shaft of the armature fits tightly in sleeve bearings, it will be difficult to turn the armature by hand. In this case the bearings should be reamed so that they fit the shaft without binding. Often, however, the fault lies in the assembly of the motor, that is, if the end plates are not put on the frame properly.

24. Unbalanced Armature. The armature is placed on balancing ways and tested for mechanical balance. If it is found to be unbalanced, use the method described in Chapter 5, page 178 to balance the armature.

Chapter 7

DIRECT-CURRENT MOTOR CONTROL

Direct-current motor control greatly changed with the introduction of electronic drives. After years of declining demand, the dc motor, with its good speed-control characteristics, has regained some of the industrial motor market because of these drives. We shall not attempt to explain the circuitry of the electronic controls but will describe the function of these drives at the end of this chapter. Chapter 10 is devoted to electronic circuitry and solid-state motor control. The electronic controllers perform many of the same functions of the older starting boxes. In some areas, there are still many of these older starting and controlling units in service.

Chapter 4, Alternating-Current Motor Control, showed that an electric controller has many functions: starting and stopping a motor, limiting the starting current or the speed, reversing rotation, providing undervoltage protection and/or overload protection, and providing dynamic braking. Some controllers are designed simply to start and stop motors; others perform several of these operations; and still others perform all of them.

Controllers are classified in many different types, but essentially they are either manually or automatically operated, using full or reduced voltage. This chapter will describe both manually and automatically operated dc controllers and how they are connected in the motor circuit.

Small dc motors of less than one-half horsepower consume very little current and therefore can be started by placing full voltage across the motor terminals. Motors larger than one-half horsepower usually require a reduced voltage for starting. However, dc motors up to two horsepower at 230 volts can be started with full voltage, provided the voltage can be applied without damage to the motor or machine. Large dc motors cause large initial currents to flow because they have a low ohmic resistance and therefore use a reduced voltage for starting. If full voltage is applied to a large motor while it is at a standstill, the excessive current flow may damage the motor's commutator, trip a breaker, or burn out the fuse. To start a large motor, it is necessary to place a resistance unit in series with the motor so that the starting current is reduced to a safe value. Such starters are called *reduced-voltage starters*. As the motor accelerates, this resistance can be

gradually decreased. The resistance is not required after the motor has reached the desired speed because the motor is then generating a voltage that is in opposition to the impressed voltage, thereby preventing excessive current flow. This opposing voltage is called *counterelectromotive force* (counter e.m.f.), and its value will depend on the speed of the motor, which is greatest at full speed and zero at standstill.

For example, if the armature of a 230-volt motor has a resistance of two ohms, the current flow at standstill will be, according to Ohm's law

$$I = \frac{E}{R} = \frac{230}{2} = 115 \text{ amp}$$

Amperes = I
Volts = E
Resistance = R

If the motor is running and thus is generating a counter e.m.f. of 100 volts, the total voltage in the armature will be 230 − 100, or 130 volts. Therefore the current is

$$I = \frac{E}{R} = \frac{130}{2} = 65 \text{ amp}$$

The flow of current has been reduced considerably by the counter e.m.f. If the motor is running at full speed and is generating a counter e.m.f. of 200 volts, then the current will be

$$I = \frac{E}{R} = \frac{230 - 200}{2} = 15 \text{ amp}$$

In other words, this motor normally will pass 15 amp at full speed. However, if the initial current is not restricted until the motor reaches full speed, 115 amp will flow—enough to burn out the motor or do considerable damage. To prevent the large initial current, resistance is inserted in the motor circuit and is gradually decreased as the motor accelerates and generates the counter e.m.f. The resistance is mounted in a box, called a *starting box,* which is mounted near the motor. A typical starting box or reduced-voltage manual starter as it is often called, is illustrated in Figure 7-5.

MANUAL CONTROLLERS

Three-Point Starting Box Connected to a Shunt Motor

A three-point starting box consists essentially of a tapped resistance element that limits a motor's starting current to a safe value. This type of starter can be used

for starting either a shunt or a compound motor. The resistance unit is tapped at various points, and the connections are brought to contacts on the face plate, as shown in Figure 7-1. When the handle is moved from point to point, the resistance in the circuit is decreased. A coil located on the face plate acts as a magnetic holding coil and keeps the handle in place after it has been moved to the last contact. The starter derives its name from the fact that three terminals are located on the face plate. These are marked L, A, and F, signifying, respectively, line, armature, and field, and are connected internally to the handle, resistance, and holding coil.

The operation of the starter shown in Figure 7-1, when connected to a motor, is as follows: When the handle is brought to the first contact point, current will flow from L_1 to terminal L and through the handle to the first contact point. From this point the current has two paths, one through all the resistance to terminal A and the other through the holding coil to terminal F. From the armature terminal, the current flows through the armature to L_2. From the field terminal, the current flows through the shunt field also to L_2, as can be seen from Figure 7-2. Because all the resistance is in series with the armature at the starting position, the initial current will be limited to a safe value. As the handle is moved up, the motor will accelerate and produce a counter e.m.f., which will also restrict the current flow.

It should be noticed that when the handle is moved to the last contact point, the starting-box resistance is entirely removed from the armature circuit and that it has been gradually placed in the field circuit. This will have no effect on the motor's performance because the resistance of the starting box has a very low value in comparison with the resistance of the shunt field. Note also that the holding coil is connected in series with the shunt field. Therefore, current will flow through it when the field is excited, energizing it and causing it to become a magnet. Thus the holding coil retains the handle in position.

Should the shunt field open for any reason, the current will stop flowing in the holding coil. Spring action will cause the handle to fall back and open the circuit to the armature. The holding coil therefore acts as a safety device, because under ordinary conditions a shunt motor with an open field circuit will tend to "run away." Because of this safety measure, the holding coil is given the name of *no-field release*.

Three-point starting boxes can also be connected to compound motors. Figures 7-3 and 7-4 illustrate this connection. The only difference between this connection and the one for the shunt motor is the addition of the series field. A manual reduced-voltage starter is shown in Figure 7-5.

Four-Point Starting Box Connected to a Compound Motor

There is very little difference between the three-point and four-point starting boxes. The main difference is that the holding coil is connected across the line in series with a resistor in order to limit the current in the holding coil, as shown in

Figures 7-6 and 7-7, instead of being connected in the shunt-field circuit. The four-point box has four terminals on the face plate instead of three. The line leads are L_1 and L_2; the armature is A; and the field is F.

When the handle is brought to the first contact point, current will flow from L_1 to the handle and to the first contact point. From here the current has three paths, which can be followed in Figure 7-7: One path is through the resistance to the armature terminal, to the armature and series field, and out to L_2. Another path is from the field terminal to the shunt field and out to L_2. A third circuit is through the holding coil, the holding-coil resistor, and back to L_2. Because the holding coil is connected directly across the line and thus cannot hold the handle in place should the voltage fail, it is given the name of *no-voltage release*.

An advantage of this box over the three-point box is that a variable resistance can be placed in the shunt-field circuit in order to increase the motor speed. A disadvantage is that the speed may increase to a dangerous degree if too much resistance is added, because this is similar to running with the field circuit open. A diagram of a four-point box with an additional resistance in the field circuit is shown in Figure 7-8. In the diagrams, the terminals have been located at convenient points on the face plate in order to simplify the diagram. In actual starters the terminals are generally placed in a row on either the bottom or the top of the face plate.

Four-Point, Speed-regulating Rheostat

The four-point, speed-regulating rheostat is a device for regulating a motor's speed. The connections of a four-point rheostat are similar to the previous four-point box, except that the field resistance is incorporated in the same box as the armature resistance, as shown in Figure 7-9. The size of resistance wire in the armature circuit must also be larger than the previous box, because the handle has a ratchet that permits it to be held stationary on any contact point by the holding coil. Because the resistance may be in the circuit at all times, it must be heavy enough to pass the armature current without heating excessively.

In operation, when the handle is brought to the first contact point, the holding coil becomes energized and attracts the pivoted arm so that it holds in the first notch of the ratchet. This maintains the handle in place without the necessity of holding it by hand. At the same time the current flows through all the armature resistance to the armature and series field and back to the line. The current also travels through the solid copper bar located above the armature resistance contacts to the shunt field and back to L_2.

As the handle is moved up to point *5*, all the armature resistance is cut out, and the field resistance is about to be cut in. This will increase the motor's speed until the last contact point is reached. It should be remembered that the handle can be left in any position desired.

Four-Point Starting-Box and Speed-regulating Rheostat

The four-point starting-box and speed-regulating rheostat is a combination starting box and speed regulator. This type of starter has a special handle (shown in Figure 7-10)—actually two arms, one under the other. When the handle is moved up, both arms are interlocked. After the handle is brought to the last contact point, the holding coil maintains in position the arm that contacts the armature resistance points. If it is desired to increase the speed above normal, the handle is moved in a counterclockwise direction. This moves only the arm contacting the field resistance and cuts in resistance in the field circuit, as shown by Figure 7-11.

When the arm is in the OFF position, the shunt-field resistance is shorted by means of an auxiliary contact located on the face plate. This contact is movable, so that when the handle is rotated to the uppermost position, the auxiliary contact opens the shorted field resistance and allows it to be used in the field circuit. At the same time, the holding coil is connected in the circuit. The object in shorting the field resistance is to prevent its use until all the armature resistance has been cut out.

In operation, the handle is moved to the first contact point, and a circuit is formed from L_1 to the handle, through all the resistance, through the armature circuit, and back to L_2. Also a circuit is completed from the first contact button through the auxiliary contact to the field terminal, through the shunt field, and back to the line. After the motor accelerates and the handle is brought to the last contact, the auxiliary contact permits the field resistance to enter the circuit and also closes the holding-coil circuit that holds the handle in position. If increased speed is desired, the arm that contacts the field resistance is moved in a counterclockwise direction, inserting resistance in the field circuit, and in turn causing an increase in speed. When the main switch is opened, a coiled spring at the base of the handle returns it to the OFF position.

Another combination starter and speed regulator that operates on the same principle as the previous box does but whose construction is somewhat different is shown in Figure 7-12. The handle of this starter consists of two arms, a main arm, and an auxiliary arm. The main arm rides on two sets of contact buttons, one set for the field resistance and the other for the armature resistance. Only the armature resistance is in the circuit as the handle is moved upward. The auxiliary arm during this operation is in such a position that it short-circuits the shunt-field resistance, causing it to be inoperative during the period in which the armature resistance is cut out.

When the main arm is brought to the last contact point, the auxiliary arm connects the armature terminal directly to the line and also allows the field resistance to be put into the circuit. The auxiliary arm is held in this position by its holding coil. If the motor's speed is to be increased above normal, the main arm is moved in a counterclockwise direction, thereby inserting resistance in the field circuit. If the main arm is brought back to the starting point, the holding coil

will be disconnected, the auxiliary arm released, and the entire motor disconnected from the line.

Reversing Motors Connected to Three- and Four-Point Starting Boxes

In Chapter 6, Direct-Current Motors, it was mentioned that there are two methods of reversing the direction of rotation of a dc motor, namely, by reversing the current through either the armature or the field. The conventional method is to reverse the current through the armature. In the manually controlled starters, a double-pole, double-throw switch, connected as shown in Figure 7-13, is used for this purpose. Other devices are also used, but essentially they are alike in that their primary purpose is to reverse the current in the armature circuit. Figures 7-14, 7-15, and 7-16 are diagrams of a series motor reversed by connecting a double-pole, double-throw switch in the armature circuit.

A shunt motor is reversed in the same manner, that is, by connecting a reversing switch in the armature circuit, as shown in Figures 7-17 and 7-18.

The connection diagram for a compound motor is similar to that of the series motor, with the addition of the shunt field which is connected across the line. When a compound motor is to be connected to a reversing switch, it must first be connected as a series motor and then connected with the shunt field across the line, as illustrated in Figure 7-19. If six leads are brought out of the motor, care must be taken to connect the motor for cumulative operation. If five leads are brought out, the lead, which is the combination series- and shunt-field wire, should be brought to one line. If an interpole motor is reversed, both the armature and interpole must be reversed as a unit. A precaution to be observed when reversing a motor is to allow it to come to a full stop before attempting to operate it in the opposite direction.

Connecting a Reversing Switch in the Armature Circuit of a Shunt Motor Connected to a Three-Point Box. A diagram of the connection of a double-pole, double-throw switch and a three-point box to a shunt motor is shown in Figure 7-20. This is similar to the circuit of Figure 7-17, except that a three-point box is in the circuit. To reverse this motor, the main switch is first opened. This causes the motor to come to a complete stop and also allows the handle of the box to drop to its OFF position. The reversing switch is then thrown, the main switch closed, and the handle slowly raised.

Compound Motor—Three-Point Box. To connect a compound motor for reversing, connect it exactly as shown in Figure 7-20, except for the addition of the series field as shown in Figure 7-21. Note in this diagram that the armature and interpole are reversed as a unit. If only the armature is reversed, sparking will occur at the brushes, and the motor will overheat.

Shunt Motor—Four-Point Box. To connect a shunt motor to a four-point box and reversing switch, it is necessary only to connect it, as shown in Figure 7-20 with a three-point box, and then to add the wire for the additional line terminal on the four-point box, as shown in Figure 7-22.

Compound Motor—Four-Point Box. If a compound motor is to be connected to a four-point box and reversing switch, it should be connected as shown in Figure 7-23.

Reversing Small Motors by Means of a Drum-type Switch. In appearance, a drum switch resembles the drum controllers used on cranes, but it is much smaller in size. It is totally enclosed, with a handle on top, as shown in Figure 7-24, and it has an outlet on the bottom to permit conduit connections. When the motor is not rotating, the handle is in the center position. When rotation is desired, the handle is moved to the right. To reverse the motor, the handle is first brought to the center until the motor stops and then is moved to the left.

Removing the switch cover will reveal the terminals to which the line and motor connections are made. If the contacts are inspected, it will be found that there are two stationary sets arranged as illustrated in Figure 7-25. These consist of four contacts on both sides of the switch, attached to and insulated from its frame. The movable contacts shown in Figure 7-26 are attached to an arm that runs through the middle of the switch and are so placed as to contact the stationary points when the handle is moved in either direction.

When the motor is at rest, the movable contacts do not touch the stationary contacts. However, when the motor is running, one possible position of the contacts is as shown in Figure 7-27. For reverse rotation, the contacts are as shown in Figure 7-28. To connect this switch to a series motor, as shown in Figure 7-29, the armature wires are connected to contacts *3* and *4* and the series field to *5* and *7*. The line wires are connected to *2* and *8*. Figure 7-29 shows the connection for counterclockwise rotation, and Figure 7-30, the connection for clockwise rotation.

For a shunt motor, the armature is connected exactly as before. The shunt field, however, is connected to contacts *1* and *7*. Contacts *5* and *7* are connected together. Figures 7-31 and 7-32 show the current paths for forward and reverse.

The compound motor is a combination series and shunt motor, and therefore the connection diagrams of Figure 7-33a and b show both the series and shunt fields connected as in the previous diagrams. The schematics in Figures 7-29, 7-30, 7-31, 7-32, 7-33a and b show the standard terminal marking combination used for the given rotations.

Overload Relays

To protect the motor and line from accidental or prolonged overloads, the starting box, the motor, or both can be equipped with a device that will automatically

disconnect the motor from the source of current when such a situation occurs. If too large a current flows for too long a time, the motor will be damaged, or the line will be disturbed. This necessary protection can be provided by fuses, by magnetic or thermal circuit breakers, or by overload relays.

Fuses are often used in the line circuit supplying electric motors. Fusible-power disconnect switches protect against short circuits. If there often are faulty currents in the circuit, circuit breakers should be used. A circuit breaker can be quickly reset after the fault has cleared.

Magnetic Circuit Breakers. A magnetic circuit breaker provides a quick and effective means of opening the motor circuit if an excessive current flows. It consists of a coil of wire sufficiently heavy to carry the motor current and is connected in series with the line. It is located in a position close to the main contact arms, as shown in Figure 7-34.

If an overload occurs, enough current will flow through the coil to energize it and cause a plunger located in the center of the coil to rise and trip the main contact arms, thus opening the circuit. These circuit breakers can be adjusted to operate between certain ranges of current. Magnetic circuit breakers of many different designs are used, but the principle of operation is the same for all. Some circuit breakers are constructed so that breaking will occur only after the overload has been sustained for a certain length of time. Breakers of this type use a unit called a *dashpot* or employ thermal elements.

Thermal Circuit Breaker. A thermal circuit breaker operates on a principle entirely different from that of the magnetic circuit breaker. Coils are not utilized in this type of breaker, but rather a bimetallic or other thermal unit is used to break the circuit. The principle of operation of the bimetallic unit depends on the expansion rates of different types of metal when they are heated. When two metals having different coefficients of expansion are welded together and heated, the unit will deflect and trip two normally closed contacts, which in turn will open a holding-coil circuit causing the main contacts to open.

Magnetic Overload Relay. Magnetic overload relays are used on both manual and automatic starters. On some of the older manually controlled starters, such as the three- and four-point starting boxes, the overload relay takes the form of a magnetic coil that is connected in series with the main line, as in the case of the circuit breaker. The circuit breaker is so designed that when a normal or slightly above normal current is flowing, there will be no effect on the overload coil. However, if there is an overload, causing an excessive current to flow, the coil will become sufficiently energized to lift a small arm, which in turn will short-circuit two contacts. If these contacts are connected directly to the terminals of the holding coil of a three-point box, as shown in Figure 7-35, current that normally flows through the holding coil will now bypass it. This causes the coil to become deenergized, releasing the handle of the box and shutting off all current to the motor.

A plunger type of overload relay is shown in Figure 7-36. When the current through the coil reaches the value set by the adjustable screw, the plunger is drawn up and opens two contacts. This type of relay can be used on both the manual and automatic controllers. If it is used on manual starters, it is connected as shown in Figure 7-39. Relays are equipped so that they may be reset either automatically or manually. On automatic or semiautomatic starters, an overload relay can be used to open the contacts of the magnetic switch or contactor shown in Figure 7-37. The overload relay open-circuits the holding coil of the magnetic contactor, causing the arm to fall back and open the line circuit. Contactors are discussed in detail on page 224.

The magnetic switch or contactor is usually shown in one of the simple forms illustrated in Figure 7-38 when it is included in a circuit diagram. Figure 7-39 shows a controller diagram using a magnetic contactor and overload relay.

The operation of this circuit is as follows: When the switch is turned on, current will flow from L_1 through the snap switch, the holding coil, the overload coil contacts, and back to L_2. The holding coil will be energized, closing the contactor. If the overload is sustained, the overload coil plunger will rise and open the relay contacts. This will open the holding-coil circuit, deenergizing the coil and allowing the handle to drop. If the starting box handle is on the uppermost contact point at the time of overload, opening the magnetic switch will cause the handle to drop. Note that a snap switch is used to close the magnetic contactor in the diagram. A START-STOP pushbutton station may also be used if the contactor is supplied with an auxiliary contact for three-wire control.

Thermal Relays. Most overload relays used on modern controllers are thermally operated. One type of relay consists of two strips of metal having different degrees of thermal expansion, welded together. If this bimetallic strip is heated, it will deflect sufficiently to trip two normally closed contacts which in turn will open-circuit the holding coil of a magnetic contactor, causing the main contacts to open. The bimetallic unit is usually heated by placing it near a heating coil or heating unit that is connected in series with the line. If an excessive current or prolonged overload occurs in the motor circuit, the heating unit will become hot and transfer its heat to the bimetallic unit, which in turn will bend and open the contacts. An advantage of the thermal relay is that it provides a time delay that prevents the circuit from being opened by momentary high starting currents and short overloads. At the same time, it protects the motor from prolonged overloading. These relays are manually reset or automatically. An illustration of one type of bimetallic overload relay is shown in Chapter 4, page 147.

Another type of thermally operated overload relay is the solder-ratchet type. They relay spindle is heated by motor current flowing through the heater element surrounding the spindle. The overload relay trips when the melting (eutectic) alloy has reached a fixed predetermined temperature. A sustained current, greater than the rating of the heater element, will raise the temperature of the spindle above the melting point of the eutectic solder that holds the ratchet wheel to the spindle. The ratchet wheel is then free to turn, allowing the relay to trip

and open its contacts. About two minutes are required before manual resetting. An illustration of this type of overload relay is shown in Chapter 4, page 147.

The usual method of denoting a thermal overload relay is to show a normally closed contact next to an overload heater symbol, as illustrated in Figure 7-40. A diagram showing an application of a thermal relay is presented in Figure 7-41.

DC Magnetic Contactor

Direct-current contactors are compact magnetic switches suitable for the remote control of lighting circuits, power (motor) circuits that have separate overload protection, battery-charging circuits, and other similar applications requiring a safe and convenient means of interrupting such circuits. Contactors do not have overload relays.

Magnetic contactors may be single, double, or triple pole in construction. In any case, only one coil is necessary to close the contacts of the switch. Figure 7-42a shows the main parts of a single-pole magnetic contactor of the clapper type which consist of a holding coil, movable arm, main contacts, and auxiliary contacts. In addition, a blowout coil is located near the main contacts and is used to quench the arc that usually occurs when the main contacts are broken. This coil is wound of heavy wire and is connected in series with the main line. The magnetic field that is produced by current flowing through it reacts against a similar field surrounding the arc and causes the arc to move upward, thereby breaking it.

It can be seen from Figure 7-42a that the main contacts will make if the holding coil is energized. Only a small current is necessary to energize the coil sufficiently to attract the arms. It is obvious, therefore, that any size of magnetic contactor can be closed by sending just a small amount of current through the coil. An advantage of the magnetic contactor is that it can be controlled by a START-STOP station located at a remote point. Figure 7-42b shows another method of denoting a contactor. Another type of contactor utilizes a solenoid and plunger for closing the contacts. Permanent-magnet blowouts are used on some contactors and are usually mounted in the arc hood. Two-pole contactors usually consist of two contacts connected in series for one pole and a single contact for the other pole. These contactors generally do not have overload relays. A wiring diagram of a typical double-pole contactor is shown in Figure 7-42c.

Pushbutton Stations. A magnetic contactor is usually controlled by means of a pushbutton station. The common station consists of two buttons, a START and a STOP button. The construction is such that when the START button is pressed, two normally open contacts are closed, and when the STOP button is pressed, two normally closed contacts are opened. Spring action returns either button to its normal position when the pressure is removed. Figure 7-43 shows several ways of illustrating a START-STOP station.

To control a magnetic contactor by a pushbutton station, it is necessary only to connect the holding coil to the stations so that when the START button is pressed, current will flow through the coil, and when the STOP button is pressed, the circuit through the coil will be opened. The auxiliary contacts will maintain the current through the coil when the START button is released. Figures 7-44 and 7-45 show a circuit diagram of a magnetic contactor connected to a START-STOP pushbutton station.

In the circuit of Figure 7-46, when the START button is pressed, a circuit is formed from L_1 through the STOP button, the START button, the holding coil M, and to L_2. This energizes the holding coil and causes the main and auxiliary contacts to close. The main contacts close the circuit to the motor, and the auxiliary, or maintaining, contacts maintain the current through the holding coil when the START button is released.

If the STOP button is pressed, the circuit through the holding coil is opened, causing the main contacts to open and thereby stopping the motor. Note that the auxiliary contacts are connected across the START button.

Magnetic Starters (Full Voltage)

Magnetic starters differ from contactors mainly in that they are designed primarily for starting motors and consist of a contactor and an overload relay, usually of the manual reset type. These starters can be used only on smaller motors, up to approximately two horsepower, and when full voltage can be applied without damage to motor or machine. On this type of starter, overload, under-voltage, and no-voltage protection are provided. On a sustained overload, the relay will trip and open the solenoid circuit, disconnecting the starter from the line. Voltage failure or a severe voltage dip will also deenergize the solenoid circuit. This starter is illustrated in Figure 7-47a and b.

Quite often it is necessary to control the motor from more than one location, and this is easily accomplished by using several pushbutton stations. Figure 7-48 shows two START-STOP stations controlling a magnetic switch.

Three START-STOP pushbutton stations are connected as shown in Figures 7-49 and 7-50. It should be remembered that the STOP buttons must always be in series with one another and in series with the holding coil, so that in an emergency the motor can be stopped from any station. Any number of START-STOP stations can be added to control a magnetic starter if they are connected properly in the circuit. The important point to remember is that START buttons are connected in parallel and STOP buttons in series.

Reversing Starters (Full Voltage)

A dc motor can be reversed by reversing the current flow through the armature circuit or the field circuit. In a compound motor, this entails reversing the current through the shunt and series fields. It is therefore much simpler to reverse the

current in the armature circuit. Note in Figure 7-51 that the armature is connected in such a manner that when contacts *R* are closed, current will flow through the armature in one direction, and when contacts *F* are closed, current will flow through the armature in the opposite direction, thereby reversing the direction of rotation. A FORWARD-REVERSE-STOP station is used with this starter. It is important that the motor be brought to a full stop before the reverse button is pressed. On this type of starter the contacts are mechanically interlocked so that it is impossible for the *R* and *F* contacts to close at the same time.

Magnetic reversing starters are also constructed with electrical interlocks to give additional protection against the *R* and *F* contacts' closing at the same time. Figure 7-52a shows the control circuit of an electrically interlocked magnetic switch. Figure 7-52b shows a control circuit using front and rear contacts of the FORWARD and REVERSE buttons.

Magnetic reversing starters also come equipped with a timing relay that prevents the motor from being reversed before it comes to a full stop. In Figure 7-53 the timing relay *TR* opens the normally closed *TR* contacts. When the STOP button is pressed, the *TR* relay prevents them from closing until a specific interval of time has elapsed. The operation is as follows: When the REVERSE button is pressed, current flows from L_1, the STOP button, REVERSE button, forward interlock, reverse coil, and to L_2. All normally open *R* contacts close, including the reverse holding contacts and the reverse timing contact. The normally closed *R* interlock opens. When the reverse timing contacts close, coil *TR* is energized, opening the normally closed *TR* contacts, thereby making both the FORWARD and REVERSE buttons inoperative, while the motor is running. When the STOP button is pressed, timing contacts *TR* remain open until the *TR* relay has timed out. This prevents reversing the motor until it has come to a full stop.

Jogging. In the event that it is desired to run the motor for a very short interval of time, an additional button is added to the station. With this button it is possible to run the motor only while the button is depressed. When pressure is removed from this button, the motor will stop automatically without pressing on the STOP button. With this arrangement the motor can be made to run momentarily. Just as in other stations, the STOP button must be in the holding-coil circuit in case it should be necessary to use it. A circuit having a START-JOG-STOP station connected to a magnetic switch is shown in Figures 7-54 and 7-55.

The operation of the circuit of Figure 7-54 is as follows: Pressing the START button completes a circuit from the positive line through the START, JOG, and STOP buttons, the overload contacts, the holding coil, and to the negative line. The holding coil becomes energized, the main contacts close, and the motor starts. The auxiliary contacts also close, maintaining the current in the holding coil after pressure is removed from the START button. Pressing the STOP button opens all contacts, and the motor stops. If the JOG button is pressed, a circuit is formed from positive through the JOG contacts, the STOP button, overload contacts, and coil to negative, closing the main and auxiliary contacts. The maintain-

ing contact circuit will open when the JOG button is pressed and will thereby be made inoperative. Thus, the maintaining circuit is broken when the JOG button is depressed.

Figures 7-56 and 7-57 show connections to a small dc motor using a JOG selector pushbutton station. The JOG button has a sleeve that can be turned to RUN or JOG. When the sleeve is turned to the JOG position, the front contacts are opened, as shown by the dotted line, thereby disconnecting the maintaining or sealing contacts. If the JOG button is now depressed, the motor will run only while pressure is held on the button. With the sleeve in the RUN position, the front contacts of the JOG button are closed, allowing the RUN button, when depressed, to complete the control circuit. This energizes coil *M*, which in turn closes the *M* contacts, sealing in coil *M*. JOG relays, described in Chapter 4, are also used in some starters and provide jogging by preventing the *M* coil from sealing in by means of contacts across the START button.

REDUCED-VOLTAGE STARTERS

Motors larger than one-half horsepower usually require resistance in the circuit at the start to limit the starting current to a safe value. As the motor accelerates, this resistance is automatically removed from the circuit in one or more steps, depending on the size of the motor and the type of controller. There are many methods of automatically removing the resistance from the motor circuit. The ones listed below will be described in detail:

1. Counter e.m.f. starter.
2. Lockout starter.
3. Definite magnetic time starter.
4. Definite mechanical time starter.
5. Drum starter.

Counter E.M.F. Starter

When a motor's armature increases in speed, the countervoltage generated in the armature also increases, thereby reducing the current in the armature circuit. Because of this reduction in current, the voltage becomes higher across the armature terminals. Therefore, if a coil designed to operate at 50 volts is connected across the armature terminals, as shown in Figures 7-58 and 7-59, it will become operative only when voltage across the armature is 50 volts or higher. The coil can be made to operate a contactor that will shunt part or all of the resistance connected in series with the armature, as illustrated by Figure 7-60. This shows the position of the accelerating contact when the motor starts.

The operation of the circuit in Figure 7-58 is as follows: When the START button is depressed, the holding coil is energized and the main contacts are closed. This completes a circuit through the starting resistance and the armature.

The shunt field is also energized. As the motor accelerates, the voltage across the armature will reach a value at which it is sufficient to energize the coil of the accelerating contactor, thereby closing the accelerating contacts. This cuts the resistance out of the armature circuit and connects the armature across the line.

Counter e.m.f. starters are also made with several steps of resistance and several accelerating coils instead of one. A three-unit type is shown in Figure 7-61. Each coil operates at a different voltage. As the voltage across the armature increases with acceleration, each coil is energized in succession, and its contacts short a starting resistance until finally the armature is connected across the line.

On some controllers, the accelerating coil is placed in series with the holding coil after the accelerating contacts have closed; on others, a resistance is inserted in series with the accelerating coil to limit the current through it. Some counter e.m.f. starters have one large coil that operates several accelerating contacts. On this latter type, the accelerating contact arms are placed at varying distances from the core of the magnet. Each arm is closed in succession as the voltage across the coil increases, and the arms in turn cut out resistance from the armature circuit.

Figure 7-62 is a diagram of a counter e.m.f. starter using relays to activate the shorting contactors across the resistors. The operation is as follows: Pressing the START button energizes contactor coil *M*. This closes the main contacts and the sealing contacts. The motor operates through resistors R_1 and R_2. Accelerating coil *1*, connected across the armature, is energized as soon as the armature counter e.m.f. reaches a predetermined value and closes accelerating contacts *1* which in turn close the circuit through coil *1A*. Coil *1A* closes contacts *1A* across R_1, eliminating this part of the resistor from the armature circuit. The armature will now speed up, the counter e.m.f. will increase and energize accelerating coil *2*, which will indirectly close *2A* and place the armature circuit across the line.

Lockout Starter

The accelerating contactors that are used in this type of controller are called *series-lockout* contactors because the accelerating coils are connected in series with the armature and are so designed that the contacts will stay open if the current through the motor is large, as at start, and will close after the motor accelerates and the current decreases. Lockout contactors are designed with either one or two coils. In either case, the coils are connected in series with the armature.

This type of controller is also known as a *current-limit starter* because the motor's acceleration is controlled by the amount of current flowing through it.

Two-Coil Lockout Contactor. Figure 7-63 illustrates one type of two-coil, series-lockout contactor. The coils of this contactor are connected in series and in series with the armature. The upper coil is the closing coil that tends to close the contacts, and the bottom coil is the lockout coil that tends to hold the contacts open. The coils are designed so that the magnetic field, or "pull," of the lockout

coil will predominate if heavy current flows through the motor. For example, when the motor starts, the contacts will be kept open by the initial current flow. As the motor accelerates and the current decreases, the pull of the upper coil will predominate and the contacts will close. This action is explained as follows:

Figures 7-64a, b, and c illustrate this type of controller with one step of resistance. When the START button is pressed, the main contacts close, completing a circuit through the closing coil, the lockout coil, the resistance, and the armature circuit. The initial current energizes the lockout coil to such a degree that the contacts are prevented from closing As the motor accelerates, the current decreases to a value at which the pull of the closing coil will predominate over the lockout coil and the contactor will close. This will short both the lockout coil and the resistance. A simple diagram of this circuit is shown in Figure 7-65. The shunt field is connected across the line throughout the controller's operations.

Controllers of this type are also made with two and three steps of resistance instead of one. One set of contacts is needed for each step. Figures 7-66 and 7-67 show a two-step controller.

If the motor is overloaded to any degree, the pull of the lockout coil may cause the contacts to open and place the resistance in the circuit. The motor will run this way until the overload is withdrawn or until the motor accelerates to the point that the current value drops. On the other hand, if there is a light load on the motor, the pull of the closing coil will close the contacts and cause the motor to accelerate too quickly.

One-Coil Lockout Contactor. A one-coil contactor is similar to the two-coil contactor in that two magnetic circuits are established when current flows through the coil. When excessive current flows through the coil, a strong magnetic field will be established that will tend to keep the contacts open. On the other hand, when a normal current flows through the coil, the magnetic field will close the contacts.

Figure 7-68 illustrates this type of contactor. Note the two magnetic paths, one through the tailpiece *B* and the other through the metallic connection *C* around which a copper sleeve is placed. If a heavy current flows through the coil, a strong magnetic circuit is set up through the tailpiece, attracting it to the extension of the coil base and thereby keeping the contacts open. When the current flow drops, the magnetic path at *C* will become stronger and cause the contacts to close. The copper sleeve limits the flux passing through *C* when a heavy current is flowing, and consequently most of the flux passes through the tailpiece.

There are several other types of single-coil lockout contactors, but all operate on the same principle of magnetic difference between two points.

From Figures 7-69a and b and 7-70 it can be seen that when the START button is pressed, the main contacts close, and a circuit is formed from positive through the lockout coil, resistance, and armature circuit to the negative line. After the initial high current has decreased and the motor has accelerated, the current through the coil will be such as to permit the accelerating contacts to close,

cutting out the resistance. The current path is then through the lockout coil and armature circuit to negative.

Figures 7-71 and 7-72 show a series-lockout controller having two steps of resistance. Its operation is as follows: Pressing the START button closes the main contacts. A circuit is now formed from positive through R_1, through lockout coil A, to R_2, the armature, and to negative. When the initial current drops low enough, contacts A close, shorting R_1 and placing lockout coil B in its place. The circuit is now through B, A, R_2, and the armature. After the armature has accelerated sufficiently, the current will fall off again, and contacts B will close, shorting out R_2 and placing only coil B in series with the armature.

Definite Magnetic Time Starter

Like other reduced-voltage starters, the definite magnetic time starter also must cut out the starting resistance in steps so that the motor can accelerate gradually. However, the accelerating contactors for this kind of starter operate on a principle different from that of the others.

The coil of the contactor has an iron core surrounded by a copper sleeve. When the coil is deenergized, the decaying flux will induce a current in the copper sleeve and cause the core to lose its magnetism slowly. This action will permit the core to retain its hold on the armature for several seconds or until the motor has had time to accelerate. On these contactors, the contacts are normally closed. When the coil is energized, the contacts open; when the coil is deenergized, several seconds elapse before the contacts close. The amount of time that the contacts remain open can be determined by adjusting the spring tension on the contactor.

Figure 7-73 and 7-74 are wiring diagrams of a starter employing this type of acceleration. An advantage of this starter over the others is that the acceleration does not depend on the motor's speed or current flow. Its operation, based on Figure 7-73, is as follows:

Pressing the START button energizes the accelerating coil, causing the accelerating contacts A to open and the auxiliary accelerating contacts $1A$ to close. This energizes the coil M, which closes the line contacts M and auxiliary contact $1M$, and opens the normally closed auxiliary contact $2M$. Closing of the line contactor establishes a circuit through the resistance and armature. Contact $1M$ provides the holding effect of the line coil, and contact $2M$, having been opened, deenergizes the coil A of the accelerating contact, which drops back after a definite time and thereby shorts the resistance from the circuit and places the motor across the line.

Definite Magnetic Time Starter with Jogging. This controller can be used for jogging by providing a JOG button in the control circuit. Figure 7-75 shows the same starter as in Figure 7-74 with the JOG button added. When the JOG button is pressed, the accelerating coil is energized, and the accelerating contacts are kept

open. The auxiliary contacts close and supply current to the line coil only while the JOG button is depressed. The holding circuit for this coil is broken when the JOG button is released.

Definite Magnetic Time Starter with Two Steps of Resistance. For larger motors, two steps of resistance are provided in the controller. Figure 7-76 shows a magnetic time starter having two accelerating contactors. The operation is essentially the same as that of the magnetic time controller except that two accelerating contactors are used instead of one. Contactor A_1 shorts out R_1, and A_2 shorts out R_2. When the START button is pressed, coil A_1 is energized, and interlock A_1 is closed. This in turn energizes coil A_2, which closes interlock A_2. Coils A_1 and A_2 open contactors A_1 and A_2, and interlock A_2 energizes coil M, which in turn closes the main contacts. A circuit is now completed from positive through the resistance, the armature circuit, and to negative. Coil M opens interlock M, which in turn opens the circuit through coil A_1, causing contactor A_2 to close, shorting out R_1. Interlock A_1 is opened when coil A_1 is deenergized; the circuit to coil A_2 is opened; and after a set time, R_2 is shorted, and the motor is placed across the line.

Definite Magnetic Time Starter with Dynamic Braking. It is important in many instances that a motor be brought to a quick stop rather than be allowed to keep running until it stops of its own accord. This can be accomplished by mechanical braking, electrical braking, or both. Elevators, cranes, and trains are equipped with a mechanical brake that will quickly stop the motor. To prevent excessive wear on the brakes and also to help stop the motor quickly, the controllers used for some of this machinery are designed to use the motor's generating action for braking purposes. This is called *dynamic braking*.

It was explained previously that a motor generates an e.m.f. opposite in direction to the impressed voltage. If to stop a motor, the main switch is opened, the motor will continue to rotate but will gradually slow down. While the motor is coming to a stop, it will generate voltage if the shunt field remains energized. If the armature is connected to a resistance during this period, the generated voltage will drive a current through the resistance and back through the armature in a direction that will tend to give the motor a torque in a direction opposite to its rotation, thereby causing it to come to a quick stop.

To accomplish this, the main contactor on a controller equipped for dynamic braking is constructed with two sets of contacts, one set of normally open contacts for the main line supply, the other set normally closed for dynamic braking. When the START button is pressed, the holding coil is energized; the main line contacts are closed; and the dynamic braking contacts are opened, as shown in Figure 7-77. When the STOP button is pressed, the main contacts open, and the brake contacts close. The current generated by the motor now flows through the resistance and into the armature, as shown in Figure 7-78. This will produce a torque in the opposite direction and cause the motor to come to a quick stop.

Figure 7-79 shows a diagram of a definite magnetic time starter with dynamic braking added. Note that the only differences between this and Figure 7-74 are the addition of a resistance, connected across the armature, and the connection of the shunt field directly across the line.

Definite Mechanical Time Starter

A dc motor can also be accelerated by mechanical definite time mechanisms. This can be accomplished by dashpot-timing acceleration and geared-timing acceleration.

Dashpot Acceleration. One type of dashpot mechanism consists of a solenoid through which an iron plunger can be made to rise when the coil is energized. Under ordinary conditions, the plunger will rise very quickly. However, if the plunger is made to ascend slowly, it can be put to use in cutting out resistance units from a motor circuit in a specified time and produce gradual acceleration.

To do this, the lower part of the plunger is attached to a piston that must rise in a cylinder filled with oil or air. When the solenoid becomes energized, the piston will be moved upward by the plunger. Its upward movement will be slow because it must force the air or oil from one compartment to another in the dashpot cylinder. This slow motion is used for shorting the starting resistance in steps, as shown by Figure 7-80. Figure 7-81 shows a wiring diagram of a starter employing this type of acceleration. Its operation is as follows:

Pressing the START button completes a circuit through the contactor coil *M*; the main contacts close. Then a circuit is formed from positive through the main contacts, all the resistance, the armature, series field, and to negative, with the result that the motor starts slowly. An auxiliary contact on the main switch closes and energizes the solenoid, which causes the plunger to rise slowly, closing contacts *1* first because they are the shortest distance apart. All the others close in succession, cutting out resistance and accelerating the motor gradually.

The reduced-voltage starters shown in Figures 7-82 and 7-83 use a fluid dashpot-timing mechanism. These starters provide time-limit acceleration. The operation is as follows: Pressing the START button energizes the line-contactor coil and accelerating coil. The line contacts close, placing resistance in series with the armature and limiting the inrush of current. At definite time intervals controlled by a time-limit dashpot device, one or more increments of resistance are shorted by the closing of the accelerating contactor.

The starter shown in Figure 7-84 is intended for heavy duty in which starting demands are frequent. Pneumatic timing mechanisms are used with this starter. Pressing the START button energizes coil *M*, closing the main line contactor and placing resistance in series with the armature. After definite time intervals, coils *1A* and *2A* become energized, closing contacts *1A* and *2A* and thereby eliminating the starting resistance from the armature circuit. Figure 7-85 is another diagram showing timed acceleration.

Adjustable-speed motors are usually equipped with a field accelerating relay. This relay provides full field during normal acceleration to base speed, and it also limits the current drawn by the armature in going beyond the base speed under field-weakened conditions. The coil of the relay is connected in series with the armature, as shown in Figures 7-86 and 7-87. When the current drawn by the armature during acceleration or under field-weakened conditions becomes excessive, the field-accelerating relay coil closes the contacts across the field rheostat, thereby placing the shunt field directly across the line. The shunt field now has full strength and prevents excessive armature current during acceleration. Figure 7-87 also has a field failure relay, which is connected in series with the shunt field. The contacts of this relay are connected in series with the holding contacts across the START button. Field failure will deenergize the relay coil, in turn opening the *FL* contact and causing the main contact to open, thereby stopping the motor. In operation (see Figure 7-87), pressing the START button energizes coil *M*, thus closing all *M* contacts. The armature receives current through the resistance; the shunt field is energized; and the motor runs. In series with the armature, *FA* receives full current and causes contacts *FA* to close, thus putting the shunt field across the line during acceleration. Note also that the field-failure relay is in series with the shunt field. Coil *M* also closes time-delay contact *M*, in turn energizing accelerating coil *1A*. This relay closes contact *1A*, cutting out part of the resistance in the armature circuit. Accelerating coil *1A* also activates time delay *1A*, thus energizing accelerating coil *2A*. This coil closes contact *2A*, eliminating the accelerating resistance.

Geared-Timing Acceleration. A geared timer is similar to a dashpot timer in that it has a plunger that is moved upward when a solenoid coil is energized. The timer is so constructed that several contact fingers will make in succession as the plunger rises. However, the amount of time between the closing of each finger is governed by a simple adjustable pendulum similar to the escapement of a clock. When the plunger rises, the accelerating fingers try to close. This exerts a torque on the mechanism's gears and causes them to rotate. The escapement allows the gears to turn only at a certain rate, so that the accelerating fingers will close at definite time intervals and in sequence. This type of controller is shown in Figure 7-88a and b.

The upper half of the solenoid is energized through a normally closed interlock when the START button is pressed. As the line contacts close, the interlock opens and inserts the lower half of the coil in the holding circuit. The accelerating fingers of the multifingered contactor close in sequence and connect the motor across the line.

Geared Timer with Dynamic Braking. Another type of starter, similar in many respects to the diagram of Figure 7-88, but with dynamic braking, is shown in Figure 7-89. The dynamic-braking circuit uses the starting resistance for braking purposes. When the START button is pressed, the solenoid coil is energized and

immediately closes the main contacts and opens the dynamic braking contacts *4*. This allows the current to flow from positive through contact *1*, all the resistance, through the motor, and to negative. Timing of the geared mechanism closes contacts *2* and *3* in sequence and puts the motor across the line. When the STOP button is pressed, contacts *1*, *2*, and *3* open, and contact *4* closes, putting the starting resistance across the armature and stopping the motor. The dynamic-braking relay keeps the solenoid coil from closing until the motor has completely stopped.

Drum Controller

Drum controllers are manual switches used for trains, hoists, cranes, machine tools, and other applications in which it is necessary to cut out resistance from the motor circuit. The general type of drum switch is usually made for reversing and accelerating. However, these switches are also designed to include other operations such as braking and field acceleration. In appearance, the drum controller is similar to the drum type of reversing switch described earlier in this chapter, except that it is larger and contains more contacts. Inside the switch there is a cylinder on which is located a series of contacts, each insulated from one another and from the cylinder. These contacts are called the *movable contacts*. There is also a series of stationary contacts located inside the controller, but not on the rotating cylinder, so arranged as to make contact with those on the cylinder as it is rotated. On top of the controller is a handle that can be moved clockwise or counterclockwise for either direction of rotation of the motor. The handle may be held stationary in any desired position in either the forward or reverse direction by means of a roller and a grooved wheel. At each successive position of the handle the roller drops into the grooved wheel and keeps the cylinder from moving either way until moved by the operator.

Arcing usually occurs when the contacts are moved from one position to another. To reduce arcing, blowout coils are provided in many controllers. Shields made of asbestos or other flame-resistant material are placed between contacts to prevent arc-overs. These arc shields also prevent short circuits caused by arcing. The shields are removable and easily replaced.

A simple type of drum controller having two steps of resistance is illustrated in Figure 7-90. The diagram shows the controller rolled flat. There are two sets of movable contacts and one set of stationary contacts. For forward direction, one set of the movable contacts makes contact with the stationary set. For the reverse direction, the other set of movable contacts is in the circuit. Note that there are three forward positions and three reverse positions to which the handle can be set.

The controller operation is as follows: In the first position, movable fingers *a*, *b*, *c*, and *d* of Figure 7-90 contact the stationary contacts *7*, *5*, *4*, and *3*. The current travels from *7* to *a*, to *b*, to *5*, and through the armature to *4*. From *4* the current flows through *c*, and *d* to *3*, through all the resistance, to the series field,

and to negative, giving the connections shown in Figure 7-91. On the second position, part of the resistance is cut out. The third position removes all the resistance from the circuit and places the motor across the line. The shunt field is across the line at all times.

TROUBLESHOOTING AND REPAIR

The procedure in locating trouble on dc controllers is similar to the procedure used for ac controllers, and a review of Chapter 4, Alternating-Current Controllers, will be found helpful in locating trouble on dc magnetic controllers. Typical troubles that occur in manual dc controllers are given below.

1. If the motor does not start when the handle is moved several points, the trouble may be:
   a. Open fuse, breaker, or relay.
   b. Open resistance unit; test by placing a 115-volt test lamp across adjacent contact points; the lamp should light; if it does not, the resistance between the two points is open.
   c. Poor contact between the arm and the contact points; arcing may occur.
   d. Wrong connection on starter. (This may occur on four-point boxes when the starter is first connected; if the two line terminals are not connected properly, the motor will not start, but the handle will hold if brought to the last point.)
   e. Broken wires may cause open circuits in the armature or field circuits.
   f. Low voltage.
   g. Excessive load.
   h. Loose or dirty terminal connections.
   i. An open holding coil in a three-point box; this will cause an open field circuit.
2. If the handle does not hold when it is brought to the last point, the trouble may be:
   a. An open holding coil, due to burn-out, broken leads, or poor contacts.
   b. Low voltage.
   c. Shorted coil.
   d. Wrong connection.
   e. Overload contacts open.
3. If the fuse blows when the handle is moved up, the trouble may be:
   a. Grounded resistance units, contacts, or wires.
   b. Handle brought up too quickly.
   c. Open shunt-field circuit on starting box; in a three-point box, the trouble may be in the holding coil.
   d. Resistance shorted out.
4. If the starting box overheats, the trouble may be:
   a. Overloaded motor.
   b. Handle brought up too slowly.
   c. Shorted resistance units or contacts.
5. If a magnetic switch is used in conjunction with the manual starter, consult the troubles as listed at the end of Chapter 4.

Electronic Controls. The basic function of the dc electronic control is to convert ac to dc. Figure 7-92a shows a single-phase sine wave and b the way it looks converted to dc. Figure 7-93a shows a three-phase sine wave and b shows the way it looks converted to dc. Figure 7-94 shows how dc voltage from a battery looks. Both the single-phase and the three-phase sine wave show an uneven voltage when compared with the battery voltage. This is called the ripple effect or the ac component of the converted voltage. As explained in Chapter 1, inductive reactance is the result when a change in voltage occurs across a coil of wire in the winding of a motor.This ac effect causes some of the older dc motors to overheat, because many of the older motors have solid-iron pole shoes. If the pole shoes are laminated, the motor should perform satisfactorily.

Single-phase–powered dc controllers are designed to handle motors ranging from one-half to five horsepower. The purpose of the device is to regulate the motor's armature voltage, the motor's speed, and the motor's current, which in turn regulates the torque.

There are two types of circuitry in these controls. One is the power or the armature circuitry. This circuitry is designed for the high current output that is needed to start and pull the load. The second is the regulatory circuitry that controls the power or armature circuitry. It is the regulatory circuitry that controls all the functions such as controlled starting and stopping, jogging, and speed control. The various functions are built into module boards that can be plugged into the main body of the control board. This same control circuitry is used for the full range of horsepower. The size of the power circuitry is determined by the horsepower. Figure 7-95 shows a single-phase–powered dc controller. The functions of some of the modules are as follows:

JOG-SPEED MODULE. This module provides a momentary jog function at an adjusted speed from zero to 50 percent of the motor's base speed.

PRESET-SPEED MODULE. This module allows for a preset-speed adjustment for continuous operation from zero to 100 percent of the motor's base speed. The armature current is automatically adjusted to the load.

SHUNT-FIELD SUPPLY BOARD. This module provides the shunt-field current and control for dynamic braking.

MINIMUM-SPEED ADJUSTMENT MODULE. This module is designed to control the motor's speed from zero to 50 percent of base speed and works with the armature current control.

ACCELERATION/DECELERATION ADJUSTMENT MODULE. This module can separately adjust the time required to go from zero to maximum speed and from maximum speed to zero. If the motor stops sooner than the deceleration time

setting, the control will apply the required voltage needed to maintain speed until the timing cycle is completed.

These controllers also have overcurrent protection for both the motor and the controller. These are temperature sensors that protect the components of both the motor and the controller. These controllers, and the older controllers, also provide electronically for field-loss protection. Figure 7-96 shows how a module plugs into a regulator circuitry board.

Three-Phase–powered DC Controllers. These controllers are available in sizes from one-fourth to 1,500 horsepower. Three-phase controllers work better than single-phase controllers do because they have less ripple effect, as shown in Figure 7-94. Three-phase controllers are also produced to handle large motor loads. Figure 7-97 shows a large controller.

The circuitry of three-phase controllers or drives is much the same as for the single-phase controllers, in that there is a regulatory circuitry and a power circuitry. They also have plug-in modules that control functions according to load needs. Some of the modules' functions are the following:

TACHOMETER-REGULATED SPEED CONTROL. (These are also available with single-phase–powered dc controllers.)

DYNAMIC BRAKING. This unit converts the motor to a generator and connects the armature circuit to a resistor, slowing the load.

REGENERATIVE BRAKING. This unit converts the motor to a generator under certain load conditions and then changes the dc output to three-phase ac power. This power is added to the three-phase power line and reduces the power's cost. Many features can be custom engineered for special types of loads.

Troubleshooting and Repair. Most controllers have manuals or bulletins designed to aid the repairperson, including a troubleshooting guide that poses problems and suggests solutions. Also included in these bulletins are installation instructions, schematic drawings, and a list of recommended spare parts. This list includes complete circuitry boards, fuses, and contactors. Repairing the boards requires a background in electronics; Figure 7-98 is an example of the circuitry.

Chapter 8

UNIVERSAL, SHADED-POLE, AND FAN MOTORS

The motors discussed in this chapter are used in a variety of appliances that are in common use today.

UNIVERSAL MOTORS

A universal motor is one that can be operated on either direct current or single-phase alternating current at approximately the same speed. This motor is most popular in the fractional-horsepower size and is used on household appliances such as vacuum cleaners, food mixers, drills, and power handsaws.

Universal motors are series wound and have a high starting torque and a variable speed characteristic. They run at dangerously high speed without a load, and because of this, they are usually built into the device they drive.

There are several types of universal motors in use today. The most popular type is similar to the small two-pole series motor with two concentrated field poles. Another type of universal motor has a field winding distributed in slots, much the same as the split-phase motor. These motors are generally made in sizes varying from 1/200 to 1/3 hp, but are obtainable in much larger sizes for special applications.

Because the universal motor is similar in many respects to the dc series motor, it is advisable that the student first review Chapter 5, Direct-Current Armature Winding, and Chapter 6 , Direct-Current Motors, before studying this chapter.

Construction of Universal Motors

The main parts of the concentrated-field universal motor are the (1) frame, (2) field core, (3) armature, and (4) end plates.

The *frame* is a rolled steel, aluminum, or cast-iron shell similar to that in Figure 8-1 and large enough to hold the field core laminations snugly. The field

poles are generally held in the frame by means of thru bolts. Very often the frame is constructed to form an integral part of the machine it supports.

The *field core,* shown with other components of the motor in Figure 8-2, is constructed of laminations that are tightly pressed together and held by rivets or bolts. As shown in Figure 8-3, the laminations are designed to contain both field poles of a two-pole motor.

The *armature* is similar to that of the small dc motor. It consists essentially of a laminated core having either straight or skewed slots and a commutator to which the leads of the armature winding are connected. Both the core and commutator are pressed on the shaft.

As in other motors, the *end plates* are located on the ends of the frame and held in place by screws. The plates house the bearings, usually of the ball or sleeve type, in which the armature shaft revolves. Many universal motors contain an end plate that is cast as part of the frame. Only one plate can be removed from this type of motor. Brush holders are usually bolted to the front end plate, as illustrated in Figure 8-4.

Operation of Universal Motors

The universal motor is so constructed that when the armature and field coils are connected in series and the current is applied, the magnetic lines of force created by the fields will react to the lines of force created by the armature and cause rotation. This is true regardless of whether the current is alternating or direct.

Rewinding the Field Coils

Nearly all universal motors are two-pole machines and therefore have two field coils. Just as in the dc series motor, the field-pole windings consist of relatively few turns of wire. Thus, there may be a few hundred turns on each coil, in contrast with several thousand on a shunt-field coil.

If new field coils are to be made, proceed in the following manner:

Remove the old coils from the core. These are usually held in place by one or two pins, as shown in Figure 8-5, which are forced through a small hole in the field core and must be removed first. Some field coils are secured to the core by a thin iron clamp that extends from one side of the coil to the other, as shown in Figure 8-6. Sometimes a piece of fiber is wedged from one field coil to another, as shown in Figure 8-7. The shape of the field coils is illustrated in Figure 8-8.

Remove the tape from the coils; then record the wire size and the number of turns in each coil. Use the same size of wire with the same kind of insulation.

Flatten the coil to a rectangle, like that shown in Figure 8-9, to make a form for the new coil. Before taking measurements for the form, remove all the tape covering so that the new coil will be the same size as the old coil. If the coil is made slightly smaller, there will be difficulty in putting the coil on the core. On the other hand, if the coil is made large, it may take up too much room and perhaps prevent assembly of the end plate on the frame.

Cut a piece of wood to the dimensions of the inside of the coil. This will be the form on which the new coil will be wound. To facilitate removal of the coil after it is wound, taper the sides slightly and place one turn of insulating paper around it. To hold the coil in position while winding, bolt two sidepieces to the form, as in the assembly shown in Figure 8-10. Place the form in the lathe or winding machine and wind the proper number of turns of the right size of wire on the form. Tie the coil before removing it, using the slits cut in the sidepieces as guides. Field coils may also be wound on coil-winder heads, as shown in Figure 6-14b.

Splice flexible leads to the ends of the coil wire. Be sure to tie the leads to the coil to prevent them from being pulled out accidentally. Tape the coil with one layer of varnished cambric and one layer of cotton tape, wrapping the coil as shown in Figure 8-11. Shape the coil so that it is like the original, and then paint or varnish it. After it dries, place it on the core and secure it in the original manner.

If the coil fits tightly, be careful not to scrape the corners on the core; otherwise the wires may ground or break. It is a good practice to place insulation at the corners of the coils to eliminate this possibility. Do not pull on the leads while putting the coils in place because this can loosen or break the connections.

Connecting the Field Coils and Armature

The field poles of a universal motor are connected in series for opposite polarity, just like the poles of any dc motor. The methods of testing the field poles for correct polarity are the same as those used on dc poles, namely, the nail test shown in Figure 8-12 or the compass method. These are preferred, but another way, as explained in Chapter 6, is to connect the two fields in series without regard to polarity and then reverse the leads of one pole if the motor does not run.

As in the case of all two-pole series motors, both fields are connected in series, as described above, and then in series with the armature, as shown in Figure 8-13. Figure 8-14 shows that one line wire is brought from the armature and the other line wire from the field.

Another method of connecting the universal motor is to connect the armature between the two field coils, as shown in Figure 8-15. The end of the first field coil is connected to one side of the armature, and the other side of the armature is connected to the next field pole. This connection is found in most power tools.

Reversing Universal Motors

In a universal motor of the concentrated-field type, the direction of the rotation is changed by reversing the flow of current through either the armature or the field coils. The usual method is to interchange the leads on the brush holders. Figure 8-16 shows this motor connected for clockwise rotation, and Figure 8-17, for counterclockwise rotation.

On many universal motors, especially those in which the brush holders cannot be shifted, reversing the rotation will cause severe arcing and sparking at the brushes, because most of these motors are made for specific application and are wound for operation in only one direction. Reversing the direction will force the brushes off the required sparkless plane. The only way that these motors can be reversed without causing sparking is to relocate the leads on the commutator. This will be more fully discussed later.

Winding the Armature

Armatures for universal motors are wound in the same manner as those for small dc motors. Just as in any armature or stator, the first step in rewinding is to secure sufficient accurate information concerning the old winding to enable the repairperson to rewind the armature with the correct turns, coil pitch, lead throw, and size of wire.

Taking Data. Before data on an armature are taken, there are a few pertinent facts about universal armatures that will help in gathering the necessary information.

All two-pole universal armatures are lap wound, with the beginning and end leads of a coil connected to adjacent commutator bars, as in Figure 8-18. Most universal armatures are also loop wound, as in Figure 8-19. After one coil is wound, a loop is made, and then the next coil is wound. Nearly all universal armatures contain two coils in each slot, and there are twice as many commutator bars as slots. It also means that there are two loops for each slot. There are also one- and three-coil-per-slot universal armatures, but in this section, our discussion will be confined to two-coil-per-slot armatures.

Proceed in the following manner in taking data on a universal armature: Count and record on a data sheet the number of slots and commutator bars. Align the center of a slot with a string or straightedge and see whether it lines up with a bar or mica. Record this on the data sheet by making a drawing such as Figure 8-20. Find the pitch of the coils by counting the slots between the top completely exposed coil, and record it on the data sheet as 1 and 6 or 1 and 5, as the case may be. Figure 8-21 illustrates a 1-and-6 pitch. The pitch of the armature coils is always approximately one-half the total number of slots for a two-pole motor.

Lead Throw. All the data so far recorded have been obtained without removing any wires from the armature. The remainder of the information is gathered during the process of stripping the armature. The lead throw is the information to be secured next. This should be as exact as possible, although it may be difficult to achieve accuracy because of the varnish on the windings. This information is important if sparkless operation is desired.

The following method is used to determine the correct lead throw:

Carefully unwind several coils, starting with the top coil, and mark on the commutator exactly where the beginning and end leads of at least two adjacent

coils are located. In order to unwind the top coil, it will be necessary to pick up all of the leads over this coil. Thus as a coil is unwound to a loop, mark the slots of the coil and the commutator bar lightly with a center punch. Record whether this is the loop of the first or second of the two coils in the slot. Figure 8-22 illustrates this procedure. The leads of the coils to be taken out are still attached to the bars and are removed as each coil is unwound. As coil *7* is removed, the beginning lead of this coil can be seen attached to commutator bar *3*. This is three bars to the right of the slot in which coil *7* is wound. The commutator bar, as well as the slots of coil *7*, should be marked. This information should be recorded on the data sheet accompanied by a diagram like that in Figure 8-22. In this method it is assumed that the coils can be unwound. On some armatures, the varnish on the coils may make this impossible.

When this armature is to be rewound, the first coil is started in the marked slots, and the first lead is put in bar *3*. All loops follow in sequence.

Figure 8-22 shows that the wires are unwound in a clockwise direction, indicating that the coils were wound in a counterclockwise direction. Also, it should be noted that the coils progress to the left. This information, too, should be recorded.

The number of turns per coil is obtained as the coils are unwound, and the size of wire is measured with a wire gauge or micrometer.

Usually the armatures are varnished and baked to such an extent that it is extremely difficult to unwind the coils. This is especially true of the topmost coils. In this event the first four or five coils, or more, are cut off in order to reach a coil that can be unwound. If the coils are burned or charred, unwinding is usually a simple operation. It is necessary only to unwind a sufficient number of coils to obtain the data; all other coils can be cut and pulled out. All wedges must be removed before the coils are unwound.

Using the Growler to Obtain the Lead Throw. If the armature is not completely shorted or open, a simpler method can be used to obtain the lead data. The procedure is as follows:

Place the armature on a growler, as illustrated in Figure 8-23. If a coil is shorted, a hacksaw blade will vibrate when placed over the slot in which the shorted coil is located. If two bars are shorted, the same effect will be produced over two slots. This is the principle used to obtain lead throw.

Short-circuit two bars with a piece of wire, and then with a hacksaw blade, locate the slot that causes the blade to vibrate. Turn the armature so that this slot is on top. Short-circuit the next two bars and see whether the hacksaw blade vibrates on the same slot. If it does, mark the three bars that were used for this test, and also mark the slots of the coils that caused the blade to vibrate.

Stripping the Armature. After recording all the data, the entire armature is stripped, and all the old insulation is removed. This is done by either unwinding all the coils or cutting the wire on both ends with a hacksaw and then pushing the

wire through the slots. New insulation of the same thickness is used, but it is cut to extend above the slots about 1/4 in. and on both ends of the slot about 1/16 in.

It is important that the commutator be tested for shorts and grounds before the new winding is put on and also that slots be cut in each bar to hold the loops. Be sure that the width of the slots in the commutator is the same as the diameter of the wire with which the armature is wound.

Winding Procedure. The method of rewinding the armature of a universal motor is similar to that presented in Chapter 5. Briefly, the procedure is as follows:

Start with any slot; wind the required number of turns into the slots of the proper pitch; and make a loop. Wind the same number of turns into the same slots as the first coil, and make another loop. Wind the next two coils into the next slot. Vary the lengths of the loops so that the leads can be identified when they are placed in the commutator bars. The leads also may be identified by using sleeving of different colors on them.

Some slight differences will be found in different motors; for example, on some armatures the coils are wound in a clockwise direction, and on others they are wound counterclockwise. In addition, the coils may progress in a right-hand direction or in a left-hand direction. In some armatures, the coil leads are on the front of the winding, and on others, on the back or pulley side. Also, the leads on some armatures are found on the left side of the coil, and on others they are located on the right side. The best policy to follow is to rewind an armature exactly as it was originally wound. If the armature coils were originally wound in a clockwise direction, as in Figure 8-24, rewind them that way. If the coils were wound counterclockwise, then rewind them in that direction, as shown in Figure 8-25. If the leads or loops were originally located on the right-hand side of the coil, as illustrated in Figure 8-26, rewind them that way. This also applies to loops placed on the left-hand side of the coil, as in Figure 8-27.

Sometimes, as shown in Figure 8-28, the armature leads are located at the back of the armature, and in this case the leads are brought through the slots so that they can be connected to the commutator.

Position of the Leads in the Commutator. It is important that the position of the leads in the commutator be exactly the same as in the original winding. If the leads are placed one or two bars from the correct position, severe sparking will occur. The position of the leads is usually determined by the motor's direction of rotation and will be different for one direction of rotation from the position for another. However, some universal motors are designed to operate equally well in either direction, although most of them are made for operation in one direction.

If the motor is designed for clockwise rotation, the leads of a coil are usually placed two or three commutator bars to the right of the coil, as shown in Figures 8-29 and 8-30. For counterclockwise rotation, the leads are usually connected several bars to the left of the coil, as shown in Figures 8-31 and 8-32. For

rotation in either direction, the leads should be midway between those for clockwise and counterclockwise rotation.

If the armature coils were originally wound in a clockwise direction but are rewound counterclockwise, the motor will run in the opposite direction and spark badly. Reversing the brush leads will reverse the motor and also stop the sparking.

Distributed-Field Compensated Motors

The distributed-field compensated motor, the essential parts of which are shown in Figure 8-33, has a stator core similar to that of the split-phase motor and an armature similar to that of the concentrated-field motor. There are two types of distributed-field universal motors. One type is called the *single-field compensated motor* and has one stator winding. The other is called the *two-field compensated motor* and has two stator windings.

The two-pole, single-field compensated motor has a stator winding like the main winding of a two-pole, split-phase motor. The fields are wound into the slots of the stator in the same manner. The field poles must be of opposite polarity and connected in series with the armature. Motors of this type are also constructed with four or more poles. To reverse this motor, interchange either the armature or field leads and shift the brushes against the direction in which the motor will rotate. The extent of the brush shift ordinarily amounts to several bars.

The two-field compensated motor has two windings in the stator, a main winding and a compensating winding. These are like the running and starting windings of a split-phase motor and are located 90 electrical degrees from each other. The compensating winding is used to reduce the reactance voltage present in the armature when it is operating on alternating current. This voltage is caused by the alternating flux, and its effect is to reduce the voltage in the armature with a consequent loss in speed and power.

Stripping and Winding. When a compensated universal motor is stripped, it is essential that the slots be accurately marked so that the new winding will be located pole for pole in the same slots as the original winding. If the new winding is located one slot out of the way, severe sparking will occur. The only remedy for this is to shift the brushes or rewind it.

When this motor is rewound, the main winding is usually placed in the slots first, and the compensating winding is put over this 90 electrical degrees away. Skein or form winding is generally used for the stator coils. A connection diagram of a two-pole compensated motor is shown in Figures 8-34 and 8-35. Note that the main field, compensating field, and armature are in series.

Two poles are usually found in small motors, and four or six poles are used in the larger universal motors. The main poles are usually wound with only one or two coils per pole, and the compensating poles have three or four coils per pole.

A layout diagram of a 12-slot, two-pole motor is shown in Figure 8-36. To reverse this motor, either the main winding leads or the compensating winding and armature as a unit are interchanged. The brushes do not have to be shifted.

Speed Control of Universal Motors

The speed of a universal motor can be regulated by inserting resistance in series with the motor, by using a tapped field, or by means of a centrifugal device.

Resistance Method. The speed of small universal motors such as those used on sewing machines is varied by a small variable resistance connected in series with the motor, as shown in Figure 8-37. The amount of resistance in the circuit is varied by means of a foot pedal and may consist of a carbon pile or a resistance wire.

Another type of speed control on small universal motors, which is illustrated in Figure 8-38, consists of two carbon blocks that are manually pressed tightly together for high-speed operation. As these blocks are slowly moved apart, they allow less current to flow and consequently slow down the motor. These motors start on very slow speed because the speed switch separates the carbons at start. As the switch is moved, it causes the carbons to increase their pressure, thereby allowing more current to flow. When the carbon blocks are separated entirely, a fixed resistance remains in the circuit, as shown in Figure 8-38. The capacitor is used to reduce arcing.

Tapped Field. The speed of some universal motors is controlled by tapping one field pole at various points, as illustrated in Figure 8-39, thereby varying the field strength and consequently the speed. The field pole is wound in several sections, with different sizes of wire and taps brought out from each section. Another method is to wind Nichrome resistance wire over one field pole and bring taps out from this. The lowest speed is obtained when the entire winding is in the circuit; medium speed, when part of the field is out of the circuit; and high speed, when this winding is eliminated.

Centrifugal Device. Many universal motors, such as those used for home food mixers, have a number of speeds. Selection is usually made by a centrifugal mechanism located inside the motor and connected as shown in Figure 8-40. The switch can be adjusted by means of an external lever. If the motor runs above the speed set by the lever, the centrifugal mechanism will open two contacts and insert resistance in the circuit, which will in turn cause the motor speed to decrease. When the motor slows, the two contacts close and short the resistance so that the motor runs faster. This process is repeated so rapidly that the variation in speed is not noticeable.

The resistance is connected across the two governor contacts, as shown in Figure 8-40. Because sparking will occur with the opening and closing of these

contacts, a small capacitor is connected across them in order to reduce the sparks and prevent pitting of the contacts. As many as 16 different speeds can be obtained in this manner.

Troubleshooting and Repair of Universal Motors

Testing. Both the field winding and the armature must be tested for defects before and after assembly. The fields must be tested for grounds, shorts, opens, and reverses in the same manner as dc fields are tested. All these tests are described fully in Chapter 6, Direct-Current Motors. In the case of universal motors with distributed-field windings, the method described in Chapter 1, Capacitor Motors, is to be followed. Because the armature of the universal motor is like the dc armature, the tests are the same. Refer to Chapter 5 for the methods used in determining and locating defects in dc armatures and commutators. It should be remembered that before an armature is rewound, the commutator should be tested for shorts and grounds.

Repair. The troubles encountered in universal motors are the same as those found in dc motors. All the troubles and their remedies listed below were discussed in Chapters 5 and 6.

1. If the motor sparks badly, the trouble may be
   a. Wrong lead position on the commutator.
   b. Shorted field poles.
   c. Open armature coils.
   d. Shorted armature coils.
   e. Reversed coil leads.
   f. Worn bearings.
   g. High mica.
   h. Wrong direction of rotation.
2. If the motor runs hot, the trouble may be
   a. Worn bearings.
   b. Dry bearings.
   c. Shorted coils.
   d. Overload.
   e. Shorted fields.
   f. Brushes off-neutral.
3. If the motor smokes, the trouble may be
   a. Shorted armature.
   b. Shorted fields.
   c. Worn bearings.
   d. Wrong voltage.
   e. Overload.
4. If the motor has poor torque, the trouble may be
   a. Shorted coils.
   b. Shorted field.
   c. Wrong brush position.
   d. Worn bearings.

SHADED-POLE MOTORS

The shaded-pole motor is a single-phase ac motor varying in size from approximately 1/100 to 1/2 hp. It is used for applications requiring a very low starting torque, such as fans and blowers. A typical shaded-pole motor is illustrated in Figure 8-41.

Construction of Shaded-Pole Motors

The main parts of a shaded-pole motor are shown in Figure 8-42. These are a stator or field frame, a rotor, and end plates.

The stator is usually of the concentrated-field type and has a laminated core consisting of salient field poles on which a coil of wire is placed. The poles are provided with a slot near one end in which a solid copper coil of one turn, called the *shading coil,* is placed. Many shaded-pole motors have a slotted stator like that of a split-phase motor, in which the winding is placed in the slots.

All shaded-pole motors have rotors of the squirrel-cage type, such as are used on split-phase and three-phase motors.

On many of these motors only one end plate can be removed, the other being cast as part of the frame. The end plates are fitted with either ball or sleeve bearings.

Operation of Shaded-Pole Motors

All single-phase induction motors require an auxiliary winding to provide the motor with a starting torque. On split-phase and capacitor motors, a start winding located 90 electrical degrees from the run winding is used for this purpose. A shaded-pole motor also requires a start winding, but in this case it usually consists of just one closed turn of heavy copper wire embedded in one side of each stator pole.

On starting, a current is induced into the shaded poles from the main poles. The shading coils establish a magnetic field that is out of phase with that established by the main fields, and a shifting field is produced sufficient to give the desired starting torque. When the motor reaches speed, the effect of the shading coils is negligible. When current is induced into the shading coils, a flux is built up that opposes the flux that produced it. Because of the nature of the sine curve and its changing instantaneous values during a cycle, the shading-coil flux will tend to keep the main-pole flux in the unshaded part of the pole during the change from zero to near maximum. From this point to a similar point as the current drops, very little current is induced in the shaded coil, and as a result the main-pole flux will be distributed over the entire pole face. So far the magnetic axis has shifted from the unshaded part of the pole to the center of the pole. During that part of the sine curve at which the current drops from near maximum to zero, current will again be induced in the shaded coil, creating a strong flux, this time in the same direction as the original unshaded-pole polarity. Consequently, in

one half-cycle the magnetic-axis flux has shifted from the unshaded part of the pole to the shaded part. Actually, the shaded-pole flux has lagged behind main-pole flux during the half-cycle. Because the flux has shifted from the unshaded part of the pole to the shaded part of the pole, the motor's rotation will also be from the unshaded to the shaded part of the pole.

Shaded-Pole Windings

The ordinary shaded-pole motor has projecting field poles on which are placed the shading turns, as shown in Figure 8-43. The coils that fit over the poles are usually wound on forms like those used for winding dc field poles and universal-motor fields of the concentrated type. Leads are connected to the coil ends, and the entire coil is taped and placed over the pole. The field coils are usually held in position by means of a metal wedge placed between poles. If the metal wedge is made of iron or other magnetic material, the operation of the motor may be improved.

In rewinding, be sure to put back the same number of turns of the same-sized wire with the same insulation. Also, be certain that the new coils are the same size as the old ones, otherwise it may be difficult to slip them over the poles. It is a good practice to put insulating paper on the corners or around the core to prevent the coil from grounding.

Shaded-pole motors are made for two, four, six, and eight poles, and adjacent poles are connected for alternate polarity. A connection diagram of a concentrated-field type, four-pole, shaded-pole motor is shown in Figure 8-44.

Shaded-pole motors are also constructed with a stator similar to that used in split-phase motors. The stator has a distributed winding that is wound in the same manner as that of the split-phase motor. Instead of the solid copper ring used in the concentrated type, the shaded winding consists of coils of wire that are wound into slots. A typical layout of the main and shaded winding of a four-pole, 12-slot motor is shown in Figure 8-45, and a wiring diagram is shown in Figure 8-46. Note that the shaded winding is connected for alternate polarity and closes on itself. Note also that it occupies only about one-third of a pole side.

Reversing Shaded-Pole Motors

Some shaded-pole motors are constructed so that they can be reversed merely by throwing a switch. Most of them, however, cannot be reversed unless they are taken apart. To reverse this type of motor, disassemble the motor, reverse the stator end for end, and reassemble. Because the direction of rotation of a shaded-pole motor is from the main pole to the shaded pole, it can be seen in Figure 8-47 that the direction will be clockwise, and in Figure 8-48, counterclockwise. This method of reversing must be used if the motor is not externally reversible.

One type of shaded-pole motor that can be reversed externally has one main winding and two separate shaded windings. The stator of this motor has slots into

which the windings are placed. The main winding is usually distributed over several slots but may have only one coil per pole.

Each of the two shaded-pole windings has as many poles as the main windings, but only one shaded winding is used at a time. One shaded winding forms a pole at one side of each main pole; the other forms a pole on the other side. This is illustrated in Figure 8-49, in which a complete pole consists of one main coil and two shaded coils. A typical layout of a 12-slot, four-pole motor is shown in Figure 8-50. Figure 8-51 shows a diagram of the connections for this motor. The main poles are connected in series for alternate polarity, and so are the shading poles. When rotation is desired in a certain direction, the circuit of one shaded winding is closed, and the other is left open, as shown in Figure 8-51.

To reverse the motor, it is necessary to open the closed shaded-winding circuit and to close the other shaded-winding circuit. Thus the position of the shaded poles is changed with reference to the main poles.

Another type of reversible shaded-pole motor has two main windings and one shaded-pole winding. Figure 8-52 shows two poles of this winding, and Figure 8-53 presents a typical layout of a four-pole, 12-slot motor. The shaded-pole winding on this motor may be of the wound type, or it may have a single closed piece of copper. For clockwise direction, one main winding is used, and the other main winding is open. For counterclockwise direction, the main windings are reversed.

The procedure for testing and troubleshooting of these two motor types is the same as for other types of motors.

FAN MOTORS: SPEED CONTROL

This section deals with the methods used for obtaining a variety of speeds from different types of motors when used on fans and blowers. These motors have been discussed in detail earlier in this chapter and in the chapters on split-phase, capacitor, and three-phase motors. Only the methods of varying the speeds of these fan motors will be discussed here.

Floor-Type Fans

Either split-phase or capacitor motors are used for floor fans. The split-phase, two-speed motors are generally made with two run windings and either one or two start windings, depending on the manufacturer. Schematic diagrams of two of these motors are shown in Figures 8-54 and 8-55.

A three-speed, split-phase motor is shown in Figure 8-56. The three speeds are obtained with only three windings: one run, one auxiliary, and one start winding. The run and auxiliary windings are wound in the same slots, and the start winding is located 90 electrical degrees away. For high speed, the run winding is connected across the line, and the start winding is also connected across the line.

For medium speed, the run winding is connected in series with half the auxiliary winding, and the start winding is connected in parallel with the high-speed winding. For low speed, the run and auxiliary windings are in series across the line, and the start winding remains connected across the high-speed winding. Actually, a tap at the inside point of the auxiliary is brought out for medium speed. A centrifugal switch is connected in series with the start winding.

In another type of split-phase fan motor with two speeds, only a run winding and a start winding are necessary. A four-pole motor will be considered, although these motors are made for a variety of poles. For high-speed operation, the four running poles are connected in two circuits to produce alternate polarity in adjacent poles. For low-speed operation, the four poles are connected in series to produce the same polarity in two adjacent poles. The latter is a consequent-pole connection and will cause four additional poles to be formed between the main poles. Therefore, the motor will rotate at the slower, eight-pole speed. In both cases, the start winding is connected across the line. There are two salient starting poles with consequent-pole connection, producing four poles for both speeds. Four leads are usually brought out of the motor. A diagram of this motor is shown in Figures 1-137 and 1-138.

Two-speed capacitor motors are also used for floor fans. One type is similar to the split-phase motor of Figure 8-54, except that a capacitor is included in the start-winding circuit, as illustrated in Figure 8-57.

Another type of capacitor motor used for two-speed floor fans is the tapped-field (permanent-split) capacitor motor. This motor, illustrated in Figure 8-58, does not use a centrifugal switch. For three speeds, the auxiliary winding is tapped at the center point, and a lead is brought out for medium speed, as shown in Figure 8-59. This motor is similar to the three-speed, split-phase motor, except that the centrifugal switch is removed and a capacitor substituted. This motor is used extensively for blowers in air-conditioning systems.

Wall and Desk Fans

Wall and desk fans are of many types, and their motors range from universal through split phase, capacitor, shaded pole, and three phase. All operate on single-phase current.

The universal type has a resistance unit in the base to vary the speed and is connected as shown in Figure 8-60. A lever that extends outside the base is used to insert the resistance in the circuit.

Split-phase motors for use on wall fans are wound like the ordinary split-phase motor, but many do not have a centrifugal switch. A special type of autotransformer, located in the base of the fan, as shown in Figure 8-61, is used to change the speed and also to produce an out-of-phase current in the start winding. The primary of the transformer is tapped for different speeds and is connected in series with the main winding. The start winding is connected across the transformer secondary. These motors are usually wound for six poles.

A capacitor motor for a wall fan is shown in Figure 8-62. This contains a capacitor of approximately 1 μf in the start-winding circuit. To increase the motor's effective capacity and consequently its starting torque, the capacitor is connected across an autotransformer. The taps on the transformer permit a choice of speeds.

Fans for Unit Heaters

Unit heaters are usually suspended from the ceiling of large rooms and are equipped with a fan or blower that distributes the heat generated in the heater. The fan or blower motor is usually connected to an autotransformer for speed variation and is controlled from a snap switch connected to the autotransformer unit, as shown in Figure 8-63. The motors are generally of the single-value, permanent-split capacitor type. To decrease the speed of this type of motor, the voltage in the run and start windings is lowered by means of the autotransformer. The lower the impressed voltage is, the more slowly the motor will run.

Different manufacturers use different methods for varying the speed. On some motors only the run-winding voltage is varied, whereas the voltage in the start winding is held constant. On other motors the run winding consists of two sections connected in series across 230 volts for high speed. If a low speed is desired, the two sections are connected to 115 volts through an autotransformer. Usually, these unit-heater motors are connected for three speeds.

Many fans are made with a motor of the shaded-pole type. The speed of these motors is varied by inserting a choke coil in series with the main winding, as shown in Figure 8-64. Taps on the choke coil provide the different speeds.

Figures 8-65, 8-66, and 8-67 show the connection diagrams for a multispeed, shaded-pole motor used for fans, small blowers, and unit heaters. Speed control is obtained by means of tapped windings. Figure 8-65 and 8-66 show the internal connections, and Figure 8-67 illustrates the external connection.

Some fan motors have a three-phase, wye-connected winding but are operated on single phase. In this motor, one winding has several coils of Nichrome resistance wire, as shown in Figure 8-68, which causes the current in the winding to be out of phase with the others. Another winding is connected in series with an inductance located in the base of the fan and tapped to provide the various speeds. The third phase is connected to the line. The resistance and inductance produce the revolving field that causes the rotor to turn.

Single-Speed Fan Motors

Blower and large-fan motors are often wound and connected for three-phase current and are generally single speed. One such type, shown in Figures 8-69 and 8-70, has 48 slots and 24 coils and is connected series-wye for eight poles. The coils of this motor are placed in alternate slots, one coil occupying two complete slots. If designed for two-voltage operation, it is connected series-delta for low

voltage and series-wye for high voltage. Six wires must be brought from this motor for two-voltage operation.

Small-Motor Selector Guide

The small-motor selection guide shown in Figure 8-71 outlines the comparative characteristics of the principal standard types of motors that meet the needs of the majority of applications. The selection guide is reproduced by permission of the Westinghouse Electric Company.

Chapter 9

DIRECT-CURRENT GENERATORS; SYNCHRONOUS MOTORS AND GENERATORS; SYNCHROS; AND THREE-PHASE WOUND-ROTOR INDUCTION MOTORS

The difference between a motor and a generator should be clearly understood before the subject of dc generators is studied. It was pointed out previously that a motor is a machine that, when supplied with an electric current, can be used for mechanical work, such as running an elevator or driving a pump. A generator, on the other hand, is a machine that is driven by mechanical means, such as a steam turbine, diesel engine, or electric motor, and produces an electric current. Direct-current generators are rated in kilowatts and range in size from a fraction of a kilowatt to several thousand kilowatts. Figure 9-1 illustrates a dc generator of medium size.

DIRECT-CURRENT GENERATORS

Direct-current generators are similar to dc motors in appearance and construction. They have the same type of armature and field poles and are generally identical. For this reason, a dc generator can easily be converted into a motor; likewise, a motor can easily be converted into a generator.

Operation of the DC Generator

If a conductor is moved across the lines of force in a magnetic field, as shown in Figure 9-2, a voltage will be induced in the conductors. This voltage can be measured by connecting a voltmeter across the terminals of the conductor. If several conductors are connected in series (like turns of a coil), the value of the voltage generated will be equal to the sum of the voltages generated in each conductor. The value of the generated voltage also depends on the strength of the magnetic field and the speed with which the conductors cut the magnetic field. The stronger the magnetic field is, the greater the voltage will be; likewise, the higher the speed of cutting is, the larger the voltage will be.

If the conductor shown in Figure 9-2 is moved downward, as shown in the illustration, the current induced in the conductor will flow in the direction indicated by the arrows. When the conductor is moved upward, the current will flow in the opposite direction. This observation shows that the direction of current flow depends on the motion of the conductor. Similarly, a change in the direction of the magnetic lines of force will also cause a change in the direction of the induced current.

Figure 9-3 shows a conductor wound like an armature coil with leads connected to a two-bar commutator. If the armature is rotated, the conductor will cut the lines of force, and direct current can be obtained from the brushes riding on the commutator.

Thus, three factors are needed to generate electricity: (1) magnetic lines of force (flux), (2) a conductor, and (3) the cutting of the flux lines by the conductor.

The three methods of producing the lines of force necessary in generating electricity are

1. Use of permanent magnets.
2. Excitation of the generator field coils with direct current from a battery or small generator (separate excitation).
3. Excitation of the field coils by current from the armature (self-excitation).

The Separately Excited Generator

When the field coils are connected to an outside source of electricity, the generator is known as a *separately excited* generator. Figure 9-4 shows a two-pole shunt generator with the field coils energized by a battery. When the armature rotates in the magnetic field, current is supplied to the load.

The Self-excited Generator

Most generators use some of the current generated in the armature to supply excitation current to the fields. This type is called a *self-excited* generator. Figure 9-5 shows the shunt field connected to the armature. At standstill, the magnetic

field is due only to residual magnetism of the field core and is very weak. When the armature rotates, the conductors cut this weak flux and generate a very low voltage that will excite the field coils slightly and create additional lines of force. Because the armature now turns in a stronger magnetic flux, it will generate higher voltage and cause more current to flow to the fields, which in turn will produce more lines of force. This action continues until the field poles saturate magnetically. This process in which the voltage increases in a generator is called the *building-up process*.

There are three types of self-excited generators: the *series generator,* the *shunt generator,* and the *compound generator*.

The Series Generator. The series generator was used at one time for street lighting but is seldom encountered nowadays. The circuit of a series generator is shown in Figure 9-6. The connections are like those of a series motor with the load completing the circuit, and thus providing a current source. The armature, fields, and load all are connected in series. If the load is disconnected from the generator terminals, the circuit through the generator will be open, and consequently no current can flow through the field coils, and no voltage will be generated. If a small load such as a lamp is connected, a small current will flow through the generator. This will create a small magnetic flux, and a low voltage will be generated. If a heavier load is put on the generator, a greater current will flow, and consequently more lines of force will be produced and a higher voltage generated. Thus, as the load on a series generator is increased, the lines of force are increased, and these in turn increase the generated voltage. This is one of the characteristics of a series generator: The voltage at no load is zero, and it increases to a maximum at full load.

The Shunt Generator. The field coils of the shunt generator are connected across the armature terminals, as illustrated in Figure 9-5. The field strength, therefore, is practically constant, regardless of load. However, as the load is increased, the terminal voltage will decrease because of an increased voltage drop within the armature. One characteristic of the shunt generator is therefore that a slight drop in voltage occurs as the load is increased. The voltage at no load is maximum and decreases slightly as the load is increased.

The Compound Generator. There are several types of compound generators, the most common being the short-shunt cumulative generator. Like the dc motor of the same name, this has the shunt field connected across the armature, and the current flow in the shunt field is in the same direction as in the series field. This generator can also be connected long shunt.

Diagrams of the short-shunt connection are shown in Figures 9-7 and 9-8. This generator usually supplies constant voltage regardless of load, but its regulation can be varied by changing the number of turns in the series-field winding or by using a resistor across the series field to vary the current through it. This is called

a *diverter*. In general, the characteristic of a compound generator is a combination of the characteristics of both the series and the shunt generators.

By changing the number of turns in the series field, it is possible to obtain three types of compound generators: (1) an overcompounded generator, (2) a flat-compounded generator, and (3) an undercompounded generator. These generators are designed as such and have the desired series turns to obtain the following characteristics:

1. If the turns on the series field are increased over the number necessary to give the same voltage output at all loads, the generator will be *overcompounded*. This means that as the load is increased, the generated voltage increases. At no load, normal voltage is obtained, but as the load is increased to full load, the voltage rises approximately 5 percent. This is desirable when the generator is located some distance from the load. The rise in generated voltage compensates for the voltage drop in the line.
2. If the number of turns is decreased, a *flat-compounded* generator will be obtained. In this generator, the voltage produced at full load is the same value as the voltage at no load. This generator is used when the load is nearby, such as in the same building.
3. If the turns in the series winding are further decreased, an *undercompounded* generator will result. In this type, the voltage at no load is normal. As the load is increased, the voltage drops considerably, until at full load it is approximately 20 percent below normal. This generator is useful when a short might occur, as in a welding machine.

Differentially Connected Generators

A diagram of a short-shunt differential generator is shown in Figure 9-9. Notice in this illustration that the current in the series field is opposite to that in the shunt field. Consequently, as the load increases, the series-field strength increases, but because it is in opposition to the shunt field, the resultant flux drops rapidly. The characteristic, therefore, is normal voltage at no load and a rapidly decreasing voltage as the load increases.

Interpoles

On all of the generators mentioned, interpoles are generally used. These are connected in series with the armature, as in dc motors. The polarity of the interpoles in a generator is, however, opposite to that in a motor. The rule is that the polarity of the interpoles in a generator is the same as the main pole ahead of it in the direction of rotation. Just as in dc motors, the field poles are tested in the same manner. Either five or six wires are brought out of the generator. Figure 9-10 shows a two-pole interpole generator.

Changing a Compound Motor to a Generator

Compound motors are generally connected long-shunt cumulative. To convert this motor to a generator, it is necessary to change the long shunt to a short shunt and reverse the series-field leads. The first change is readily understandable and need not be made unless desired. The reversing of the field leads must be made for the following reason. In a generator the voltage is supplied to the fields from the armature terminals. Therefore, as shown in Figure 9-11, if the series field of a motor is not reversed, a differential generator will be produced. A short-shunt motor is shown for simplicity. In this change the direction of rotation remains the same.

Regulating the Generated Voltage

To regulate the generated voltage, a field rheostat is inserted in the shunt-field circuit, as in Figure 9-12. This arrangement makes it possible to vary the current in the shunt field, which in turn varies the lines of force. With full current in the field, the maximum voltage will be obtained. As resistance is added, the generated voltage will fall.

Measuring Voltage and Current of a Generator

A voltmeter and ammeter are used to measure the voltage and current, respectively. As illustrated in Figure 9-13, the voltmeter is always connected across the line, and the ammeter, in series with the line. The ammeter is really a millivoltmeter with an internal shunt, and actually the meter measures the voltage drop across the shunt. The shunt, however, is calibrated in such a manner that the reading on the meter indicates current flow. Often the meter is supplied with an external shunt; in this case it is connected as shown in Figure 9-14. These meters are connected in the same way for a motor, that is, the voltmeter across the line and the ammeter in series with the line.

Connecting Compound Generators in Parallel

When a load on a generator exceeds the generator's capacity, it is necessary either to decrease the load or to connect another generator in parallel with the first one, thereby dividing the load between the machines. A parallel connection of two generators is shown in Figure 9-15.

To connect two generators in parallel, the voltage of each generator must be exactly the same. This can be regulated by means of the field resistance and is measured by a voltmeter. Line wires of the same polarity must be connected together. An equalizer connection, consisting of a wire that connects the series field of both generators in parallel, is necessary. The reason for this equalizer

connection is that if generator *1*, at the left of Figure 9-16, runs slightly faster than does generator *2*, it will generate more voltage; consequently, more current will flow through the series field and cause the output of generator *1* to exceed the output of generator *2*. Generator *1* will therefore assume more of the load, and generator *2*, less. As the load on generator *2* decreases, more of the burden will be placed on generator *1* until it has taken the full load and generator *2* is running as a motor.

If an equalizer is used, the excess current of generator *1* is divided between the series fields of both generators and prevents one from assuming more of the load than the other does. This action is best described with reference to the circuit at the right of Figure 9-16. Each generator now has equal flux and therefore generates equal voltage. As a consequence they share the load equally. The shunt field has been omitted in Figure 9-16 for simplicity.

Troubleshooting and Repair of a DC Generator

Testing dc generators is similar to testing dc motors. The faults and troubles that occur in dc generators but not in dc motors are described below.

1. If it does not generate, the trouble may be
   a. Loss of residual magnetism: If the field poles lose residual magnetism, it is impossible for the armature to cut lines of force, and therefore no current can be generated. To remedy this condition, the shunt field is connected to a source of direct current for a few seconds.
   b. Too much resistance in the field circuit: Because the building-up process of a generator depends on the continued increase in the strength of the field, it is obvious that the voltage cannot build up if a high resistance in the field circuit prevents sufficient current from flowing in the field coils to increase the flux. The high resistance may be due to the field rheostat, an open circuit in the field, loose connections, poor brush contact, or broken brush pigtails.
   c. Wrong field connection: The residual magnetism in a generator produces lines of force from a north pole to a south pole. If the current in the field coils is in the wrong direction, as shown in Figure 9-17, lines of force will be produced opposite to the residual lines, and a cancellation of flux will result that will prevent the generator from building up. To remedy this trouble, reverse the shunt-field connections or reverse the direction of rotation of the generator.
   d. Wrong rotation: Wrong direction of rotation is similar to reversed field polarity because it causes the current in the shunt field to flow in the wrong direction. To correct this situation, reverse the direction of rotation or interchange the shunt-field leads.
   e. Shorted armature or field: A shorted armature or field may allow only a low voltage to build up. If completely shorted, the voltage will not increase, and the armature will smoke. If all other faults are eliminated, test the armature and field for shorts according to the method described for dc motors.

2. If the voltage drops considerably as the load is placed on the generator, the trouble may be
   a. Differential connection.
   b. Shorted armature.
   c. Overload.
3. If the voltage does not build up to a maximum, the trouble may be
   a. Wrong brush position. (Check for the neutral position, as described in Chapter 6, Direct-Current Motors; for interpole generators, the neutral point is directly under the center of the interpole.)
   b. Shorted armature or field coils.
   c. Resistance in the field circuit.
   d. Speed of generator too low.

All the troubles listed above are in addition to those usually found in a dc motor. For instance, sparking at the brushes of a generator may be due to the same causes in a dc motor. A review of Chapter 6 is essential.

SYNCHRONOUS MOTORS AND GENERATORS; SYNCHROS

A synchronous motor is an ac motor in which the rotor revolves in step or in synchronism with the rotating magnetic field produced by the stator winding. This action means that if the magnetic field of a 60-cycle, four-pole motor revolves at the rate of 1,800 rpm, the rotor will also turn at that speed.

In an ordinary induction motor, the rotor turns at a slightly lower speed than does the revolving field. This is necessary in order that the squirrel-cage winding be cut by the revolving field and thereby have a current induced in it. Because slip is defined as the difference in speed between the rotor's actual rpm and that of the magnetic field, a synchronous motor has zero slip.

Synchronous motors of the type shown in Figure 9-18 are made in sizes varying from approximately 20 to thousands of horsepower and are used wherever it is necessary or desirable to obtain constant speed. In many cases, synchronous motors are used to improve the power factor of the electrical system of a plant or factory. Many small synchronous motors are also made but are constructed differently from the large ones. The motor shown in Figure 9-18 is a brushless synchronous motor.

Synchronous Motors with Excited Rotor

Some synchronous motors have a rotor that is excited by direct current. Other synchronous motors have a rotor that needs no excitation. The first type has a stator core and winding like the stator of a three-phase induction motor. The rotor of this type has salient field poles, shown in Figure 9-19, similar to the fields of

a dc motor. The field coils that fit over the poles are connected in series for alternate polarity and have two leads brought out to two slip rings on the shaft. The field coils are excited with direct current supplied by a small dc generator or brushless exciter. On many synchronous motors, the dc generator is attached to the shaft of the motor to supply the excitation to the rotor fields. A three-phase power source is generally used for the motor stator.

A squirrel-cage or amortisseur winding is provided for starting purposes because this type of motor is not self-starting. The squirrel-cage winding is located around the rotor as it is in an induction motor.

Operation of the Synchronous Motor

When the main line switch to the stator winding of a synchronous motor is closed, a rotating magnetic field is established in the motor, which cuts across the squirrel-cage winding and causes an induced current to flow. The magnetic field of the squirrel-cage winding reacts with the stator field in such a manner as to cause rotation.

The motor will run and increase in speed to a point just below synchronism. At this speed, the rotor field coils are energized with direct current, and definite magnetic poles are formed on the rotor. These magnetic poles attempt to lock with the revolving magnetic poles of the station and, in so doing, increase the motor speed until the rotor is running in step with the revolving field.

When used for power factor correction of an ac line, the field windings are overexcited and cause the motor to draw a large leading current. This tends to correct a lagging power factor, because in a plant using many induction motors, a large lagging current is drawn. The leading current of the synchronous motor compensates for the lagging current of the induction motor. This machine, when utilized for power factor correction, is called a *synchronous condenser*.

Windings

The stator winding of the synchronous motor is identical with the three-phase, squirrel-cage motor's stator winding. The synchronous stator windings consist of a number of coils placed in stator slots and, as in a three-phase induction motor, are connected either wye or delta for a definite number of poles. Three leads are brought out of the stator winding for connection to the line, as shown by Figure 9-20.

The field coils, of which there must be as many as there are poles in the stator, are wound in the same manner as those used in dc motors. The amortisseur winding is embedded in the core of the field poles and connected on each side to end rings. It is used only for starting.

The rotor winding consists of a number of field poles joined in series for alternate polarity. Two leads are brought out and connected to two slip rings in

order that the winding can be supplied with direct current, as illustrated in Figures 9-20 and 9-21.

Brushless Synchronous Motor

The brushless synchronous motor has no brushes, slip rings, or commutator. In the previous paragraphs it was explained that a dc exciter was necessary to supply the direct current for the motor's field windings. This involved the use of brushes and commutator in the exciter, as well as brushes and slip rings for the synchronous motor. In the brushless type of synchronous motor, dc excitation is also necessary, but it is obtained from an ac generator and rectified to direct current by the use of high-current silicon rectifiers. The silicon rectifiers allow current to flow in only one direction, thus providing rectification; they also replace all sliding and mechanical contacts. These rectifiers are commonly known as *solid-state diodes* and are usually arranged in a three-phase bridge connection assembly. The motor's rectifier assembly, exciter rotor, and rotating field structure rotate with the motor's shaft, thereby eliminating the need for brushes, slip rings, and commutator.

Solid-state rectifiers and controls are explained in detail in Chapter 10. Therefore, only elementary diagrams will be shown here, and we shall not go into the theory of rectification. Figure 9-22 illustrates a synchronous motor, showing how direct current is produced for the motor field windings. The operation is as follows: The exciter field receives a dc input through a rectifier and provides the magnetic field that surrounds the rotor. The rotor generates a three-phase voltage as it revolves in the magnetic field. The exciter's output is connected to a three-phase bridge rectifier and is converted to direct current which is fed to the rotor field of the synchronous motor. The motor's stator is connected to a three-phase power source. All the components, with the exception of the exciter field and motor stator, rotate with the motor's shaft. The synchronous motor is brought up to speed by means of the damper or squirrel-cage winding on the rotor, and as it approaches synchronous speed, the rotor field coils are energized with the rectified current, causing the poles to lock in with the revolving field. Additional solid-state components are required to apply the excitation at the proper speed and to short the motor field during start-up. A rheostat in the exciter's field controls the exciter's voltage output. This may also be accomplished by means of solid-state components.

Synchronous Motors with Nonexcited Rotors

Nonexcited-rotor synchronous motors can be made for either single-phase or three-phase operations. One type comprises a stator core similar to either a split-phase or three-phase stator and a squirrel-cage rotor on which flat surfaces have been cut, as in Figure 9-23, thereby producing salient poles.

The squirrel-cage winding provides the starting torque and brings the motor to a speed at which the salient poles on the rotor can lock in synchronism with the frequency of the field current. The salient poles must equal in number the poles on the stator from which they obtain their magnetism by induction. When the motor reaches speed, the squirrel-cage winding is useless, and rotation is then caused by the rotor poles locking in step with the stator's magnetic poles. On some motors, the rotor poles are made of magnetized steel and retain their magnetism at all times.

Synchronous Clock Motors

A common type of synchronous motor extensively employed is that used on electric clocks. Most of these are self-starting, whereas some must be turned by hand to give them a starting torque. Self-starting motors are given the starting torque by means of shaded poles (shown in Figure 9-24), as in the case of shaded-pole motors. Usually these motors have two salient field poles and therefore should rotate at 3,600 rpm. However, the rotor is constructed so that is has from eight to 16 or more salient poles besides a squirrel-cage winding. Figure 9-25 shows a rotor with 12 salient poles. The motor starts when the clock is plugged in because a revolving field is set up that cuts across the squirrel-cage winding and causes the rotor to turn. When the rotor reaches synchronous speed (600 rpm for a 12-pole motor), the rotor poles, which have become polarized by the stator field, lock in with the stator magnetic field and rotate at the synchronous speed.

Another type of clock motor employs a rotor consisting of several laminations with the outer edge cut in a fashion to produce salient fields, as shown in Figure 9-26.

The stator consists of a two-pole frame with either one or two coils to produce the magnetic field. The pole pieces are also cut to form salient poles of the same size as the rotor poles.

These motors do not have shading poles and therefore are not self-starting. When the clock is plugged in, a pulsating magnetic field is established that cuts the rotor poles, magnetizing the poles on the rotor but producing no torque. However, if the rotor is given a start manually, its poles will be attracted to the stator poles and will lock in step with the pulsations of the current, thereby keeping the motor running at a synchronous speed. The number of salient poles on the stator will determine the speed, which may range from 450 rpm for 16 poles, 60-cycle current, to 225 rpm for 32 poles. Figure 9-26 shows a synchronous clock motor with 32 poles. There are other types of synchronous motors, but on the whole they are similar to those described above.

Troubles of Synchronous Clock Motors. Usually the troubles encountered on clock motors are lack of lubrication and worn bearings. Frequently a few drops of oil on the rotor bearings will put the clock in operation, but if the bearings are

badly worn, the clock may operate for only a short time under this treatment. In case the bearings are badly worn, it is necessary to have them replaced by a watchmaker. If the winding is open or burnt, it must be replaced. Rewinding the coil is difficult and expensive.

Synchronous Generators

A synchronous generator is similar in construction to the excited type of synchronous motor. It consists of a stator having a three-phase winding and a rotor with salient field poles that are excited by direct current. Whether or not it has a squirrel-cage winding depends on the use to which the generator is put.

As in the case of the dc generator, the synchronous generator may be turned over by a motor, steam turbine, or diesel engine. Three wires are brought out of the stator winding, which is usually wye connected. A fourth wire may be carried from the wye point and used as a ground wire for lighting purposes.

In operation, the generator is first brought to speed and the field poles slowly excited with direct current. As the rotor fields revolve, lines of force cut across the stator winding and cause current to be induced therein. If the stator is connected for three phases then a three-phase current will be generated. For a single phase, only two of the three wires are used, or, if wye connected, one phase wire and a wye point.

A diagram of an ac generator, also called an *alternator,* is shown in Figure 9-27. Note that is is similar to the synchronous-motor circuit of Figure 9-21. Because the frequency of an alternator depends on the machine's speed and number of poles, it is obvious that varying the exciting voltage will have no effect on the frequency, although the generated voltage will be affected by the exciting voltage. The generated voltage varies with the load, and therefore in order to keep the voltage constant, it is necessary either to adjust the exciting voltage manually or to use an electronic voltage regulator.

Brushless Synchronous Generator

The brushless synchronous generator is similar in construction to the brushless motor. The revolving elements used to supply direct current to the generator's field winding are the exciter rotor, the solid-state rectifier assembly, and the field pole windings on the generator's rotor. There is no need for slip rings, brushes, or commutator, as all these rotate with the generator's shaft. The exciter's stationary field winding is connected to a rectified ac supply. Figure 9-28 shows an elementary diagram of a brushless synchronous generator. In operation, a three-phase exciter is converted to direct current by means of a solid-state (diodes) bridge rectifier. The rectified current is fed to the generator's rotor field. As the rotor revolves, lines of force cut across the stator winding and cause current to be induced therein. In addition to rectification, there may be static voltage regulation, voltage sensing, and compensation for parallel operation. It must be re-

membered that a prime mover such as a motor or diesel engine must be used to turn over the generator.

Alternators in Parallel. Several conditions must be satisfied before alternators can be paralleled.

1. The alternators' output voltage must be equal, and the frequency must be the same. Assuming that two alternators are to be paralleled, regulate the voltage of each by adjusting the excitation voltage of the dc generator supplying current to the alternator fields and the frequency by adjusting the speed of the prime mover.
2. The polarities of the alternators must be synchronized. This operation is called *phasing out* the alternators and is performed in the following manner: Assume alternator *A* is to be phased out with alternator *B*, as in Figure 9-29. Connect three sets of lamps across the paralleling switch, as shown in the illustration. If both alternators are running at the required speed and generating the proper voltage, all three sets of lamps should go on and off at the same time, thus indicating that the alternators are properly phased out. This is called the *all-dark* method. The three-pole switch is closed when all lamps are dark. If each set of lamps goes on and off alternately, it is an indication that the machines are not in phase. To remedy such a condition, interchange any two leads from alternator *B* at the parallel switch.

Another method of phasing out is to use three sets of lamps connected as shown in Figure 9-30. This is known as the *one-dark-and-two-bright* method and is a more desirable way of phasing out than is the all-dark system. With both alternators running, the phasing-out switch is left open until one set of lamps is dark and the other two sets are bright. The switch is then thrown to close the circuit.

SYNCHROS

A synchro is a small rotating machine that is similar to a synchronous alternator. However, the salient field winding of the synchronous alternator is excited with direct current, whereas in the synchro, the field is excited with alternating current. Both machines have a three-phase winding. These machines are not used as motors and therefore are not rated in horsepower but, rather, in the torque that they exert. This is usually expressed in inch-ounces (in.-oz.). Synchros are used for remote signaling, control, or indication and must be used in conjunction with one or more similar machines. When one machine, the transmitter, is turned, the other machine, the receiver, turns a like amount, whether the transmitter is turned through a complete revolution or only one degree.

Construction of the Synchro

There are many types of synchros. The most common kind consists of a stator, shown in Figure 9-31, like that in a split-phase or three-phase inductor motor. It has a three-phase, wye-connected winding in the slots. Three wires are brought out of the stator for connection to another synchro. The rotor usually consists of a core having two salient poles, as shown in Figure 9-32. It has two field coils connected for alternate polarity. The ends of this winding are connected to two slip rings that contact brushes connected to alternating current. Synchros are also designed with the three-phase winding on the rotor and a distributed two-pole winding on the stator. Ball bearings are used to eliminate end play and provide exceptionally smooth operation.

Operation of the Synchro

Each synchro may be thought of as a transformer. The field coil acts like the primary and is connected to an ac source, and the stator's three-phase winding acts like the secondary. Because there are three windings in the synchro stator, a voltage will be induced in each phase. These voltages differ, depending on the position of the rotor with respect to the stator. If the rotor is turned slowly by hand, different voltages will be induced in the three-phase winding. Figure 9-33 shows a diagram of a synchro machine. There are five external leads, three from the three-phase winding and two from the rotor winding. Note that the rotor winding is excited by 120 volts of alternating current.

One synchro is located at the sending point as a generator or transmitter, and the other is operated at the receiving point as the receiver. The two machines are connected as shown in Figure 9-34. Note that the three-phase windings are joined to one another and that the primaries are connected in parallel to the same source of excitation.

If the rotor is in the same position in both the transmitter and receiver, then the voltages generated in the corresponding phase windings of both machines will be equal. Because corresponding phases are connected to each other, the voltages induced will oppose one another, and no current will flow.

If the rotor of the transmitter is moved from its initial position, the induced voltages of both machines will be unequal and opposite, as in Figure 9-35, and consequently current will flow from one stator to the other. This current will set up a torque in the receiver and cause the rotor to turn until it is in a position corresponding to that of the transmitter's rotor. When both rotors are in the same position, no more current will flow, and the receiver's rotor will not turn.

If the receiver turns in the opposite direction to the transmitter, it is necessary to reverse two wires of the three-phase winding. It is important that the primaries of each machine be connected to the same source of supply, or they will be out of phase and will not operate properly.

THREE-PHASE WOUND-ROTOR INDUCTION MOTOR

The three-phase wound-rotor motor ranges in size from fractional to hundreds of horsepower. They are designed for variable speed operation. Typical use for this type of motor would be pumps, cranes, and large air compressors.

Construction of the Wound-Rotor Three-Phase Motor

The main parts of the wound-rotor three-phase motor are (1) stator, (2) rotor, and (3) end plates.

The stator is constructed identically to the stator of the squirrel cage motor. There are three single-phase windings placed in the slots, 120 electrical degrees from each other. The stator windings are connected wye or delta and can be single or dual voltage.

The rotor also has three single-phase windings placed in the slots of the rotor, 120 electrical degrees from each other. The windings of the rotor can be connected wye or delta and usually are one circuit. Three leads from this winding are connected to three slip rings. Brushes ride on the slip rings and the brush leads are connected to a controller. Figure 9-36 shows a wound rotor. Figure 9-37 is a diagram of a one-wye connection used in a rotor. The rotor windings are laid out the same as stator windings; the only difference is that they are constructed to withstand the problems connected with rotation.

Operation of the Three-Phase Wound-Rotor Motor

When the stator of the wound-rotor motor is energized with three-phase power, the lines of force from the rotating magnetic field cut the conductors of the rotor, inducing or transforming a voltage into them. This voltage creates a current that has a path to the slip rings, through the brushes, and the brush leads to a controller. Figure 9-38 shows the stator and rotor circuit of this controller. The resistors of the controller complete the circuit of the wound rotor and there is a closed circuit formed for the current to follow. The resistors of the controller limit the amount of current in the rotor circuit. When contacts 1A, 2A, 3A, and 4A are closed in timed sequence, each set of contacts shorts out some of the resistance in the controller. This allows more current to flow in the rotor circuit. As resistance is eliminated from the rotor circuit, the rotor will accelerate. The motor's rated speed will be reached when all the resistors are shorted out. Top speed, like that of the squirrel-cage motor will be slightly under synchronous speed. Synchronous speed is determined by the line frequency and the number of poles in the motor. The wound-rotor three-phase motor does not have good speed regulation. If the load is removed at any step or sequence of the controller, the rotor will accelerate to near synchronous speed. The speed is controlled by the load and the amount of current allowed to flow in the rotor circuit. Speed is controlled by

varying the amount of slip. Regenerative electronic speed controllers are much more efficient than controllers that use resistors. The electronic controller can change the energy that is wasted as heat in resistors into three-phase power. This power is syncronized with line power and put back on the line, thereby reducing the power cost. The wound-rotor motor operates like the squirrel-cage motor when all the resistance in the controller is shorted out. Unlike the squirrel-cage motor, however, some wound-rotor motors will not start without some resistance in its circuit. There is a low power factor in the rotor circuit at low rpm's and the phase angle between the rotor and stator circuit is too great.

When comparing the windings of a wound-rotor and a squirrel-cage rotor, there is only one turn or conductor in the squirrel-cage rotor and there are many turns or conductors in the wound rotor. Because of many turns in the wound rotor, there is much more inductive reactance.

Low Power Factor. The delay in current flow in the wound-rotor circuit because of the high inductive reactance will cause the rotor to reach peak magnetism after the stator poles have done so. This will weaken the interaction between the rotor and stator poles and the motor will not start. Resistance will reduce inductive reactance in the rotor circuit and improve the phase angle. An improved phase angle means that the peak magnetism of the two circuits will happen at or almost at the same time. The result would be better interaction between the two circuits creating a high starting torque.

Troubleshooting the Three-Phase Wound-Rotor Motor

The stator of the three-phase wound rotor is the same as the stator of the standard squirrel-cage motor. The same test can be applied to these stators that is described in Chapter 3.

The rotor of the wound-rotor motor has the same type of windings as the stator; therefore, many of the same test procedures can be used to determine the problems described in Chapter 3. The rotor will have additional problems that are caused by inertia. When connections are not secured properly, they will flex and break. The leads that go to the slip rings are a place where openings can occur. The slip rings will heat and expand causing a stress on the lead where it is connected to the slip ring. Expanding and contracting will eventually break the lead wire. When this happens, the rotor has only two-thirds of its windings in the circuit. The motor will lose power and two-thirds of the rotor winding will burn out. If the slip rings are dirty or uneven, the brushes do not have good contact and the result is excessive heating. Many of the commutating problems found in dc motors are present in the slip rings of the three-phase wound-rotor motor.

Chapter 10

SOLID-STATE MOTOR CONTROL

The speed, position, acceleration, and deceleration of electric motors can be controlled electronically by using solid-state circuits. Speed is controlled by employing solid-state–phase circuits to limit the effective voltage supplied to appropriate elements of the motor or by controlling the frequency of the supply. Microprocessors and computers are used to control motors' position, speed, acceleration, and deceleration. These sophisticated digital circuits acting with or without feedback, can start and stop motors smoothly, position them precisely, and guide them through complicated sequences of motion. Motor-control circuits exploit the characteristics of modern solid-state devices; to understand them we must first understand these devices.

SEMICONDUCTOR MATERIALS

Semiconductor materials lie between conductors and insulators in their ability to conduct electric current. A one-centimeter cube of a good conductor, silver, for example, has a resistance of 10^{-6} ohms. A one-centimeter cube of mica, a good insulator, has a resistance of 10^{12} ohms. In contrast, a one-centimeter cube of pure silicon, the most widely used semiconductor material, has a resistance of 50 to 60 kilohms.

Semiconductor materials (germanium and silicon, for example) are crystals. Conduction in semiconductor crystals differs from conduction occurring in either insulators or conductors. This characteristic is exploited by solid-state devices. To understand semiconductor conduction, it is necessary to review the atomic structure of crystals.

ATOMIC STRUCTURE

All matter is composed of atoms. Atoms are complex dynamic structures containing a nucleus with a net positive charge surrounded by orbiting electrons that exactly cancel this charge. But semiconductor action can be explained without recourse to the atom's actual physical structure, which is not yet entirely known.

Instead, we use a simplified model called the Bohr model (Figures 10-1 and 10-2).

In the Bohr model, electrons with nearly the same energy are grouped into shells. Each shell is represented by a single circular orbit containing one or more electrons. The maximum number of electrons in any shell is fixed by physical considerations. The outermost shell is called the *valence shell.* The electrons in this shell are most easily lost or gained. Therefore this shell participates most often in atomic interactions. When this shell is filled, the atom is stable.

Crystals are composed of atoms that join to form symmetrical and repetitive patterns. These atoms complete their valence shells by sharing valence electrons with their neighbors. Silicon requires four valence electrons and combines with four neighboring atoms to achieve stability. Another less widely used material, germanium, also requires four valence electrons and bonds in the same way. In the presence of external energy (light or heat), semiconductor material is not completely stable. The external energy frees some valence electrons, leaving unfilled niches called *holes*.

A voltage applied across a slab of relatively pure semiconductor material will produce a small electric current. This current flows in two modes, *free electron* and *hole flow*. Free electron flow is similar to conduction in metal. Electrons move through the semiconductor in erratic paths, colliding with atoms and other electrons. In the aggregate they move steadily toward the positive voltage. Conduction by holes is also a result of electron movement, though it is the valence electrons that move. These electrons jump from atom to atom, filling existing holes. These electrons also move toward the positive voltage, but the holes appear to move in the opposite direction. Therefore it is convenient to think of electrons as negative carriers and holes as positive carriers. In the pure state, free electrons and holes are evenly divided and relatively few.

PROPERTIES OF DOPED SEMICONDUCTORS

The ratio of free electrons to holes in a semiconductor must be changed before it can be used in a solid-state device. This is done by adding minute amounts of impurities *(doping)*. If the added impurity contains atoms with five valence electrons, one free electron will remain after they bond to the semiconductor atoms. The added impurity is called a *donor,* and the semiconductor becomes N-type material. Impurities containing atoms with three valence electrons will form incomplete bonds with the semiconductor atoms, leaving holes. These impurities are called *acceptors,* and the doped semiconductor becomes P-type material. Figure 10-3 shows conduction in an N-type semiconductor.

P-N JUNCTION (DIODE)

When N- and P-type materials are brought into intimate contact, a P-N junction (diode) forms (Figure 10-4). Upon contact, the free electrons from the N-type

material diffuse into the P-type region, and holes leave the P-type region and enter the N-type region. The N region that loses electrons acquires a positive charge, and the P region that loses holes acquires a negative charge. Electrons fill holes around the junction, leaving a region devoid of carriers. This is called a *depletion region.* A small potential difference will now exist across the junction. This potential difference will prevent the further diffusion of electrons and holes, and the junction will stabilize in this state (Figure 10-5). An external voltage applied across the diode, as shown in Figure 10-6, will increase this barrier, and no current will flow. The diode is now reverse biased. Making the P material positive in respect to the N region (Figure 10-7), reduces this barrier and permits a current to flow. The diode is now forward biased. The magnitude of the current depends on the applied voltage.

Diode Characteristics

Diodes pass current more readily in one direction (forward bias) than in the other (reverse bias). The circuit symbol defining this action and the circuit actions of a diode are shown in Figures 10-8, 10-9, and 10-10. Forward-biased diodes may carry large currents and dissipate power. If the maximum allowable junction temperature is exceeded, the diode will be damaged. This temperature may be held down by connecting the diode leads or case to a large, finned mass of metal called a *heat sink.* Some commercial silicon diodes are shown in Figure 10-11. Small diodes (glass cases) are mounted on heat sinks by their leads. Large diodes (stud mounted) are thermally connected to heat sinks through their metal cases.

Figure 10-12 displays the voltage-versus-current characteristic of a typical silicon diode. (Note that the region below the horizontal axis is expanded.) The forward-bias characteristic is a nonlinear curve, but it can be approximated by a straight line meeting the horizontal axis at 0.7 volts. The slope of the straight line represents the *forward* or *on* resistance of the diode. This value is supplied by the manufacturer. The reverse-bias curve is initially horizontal, showing that a small constant current (microamps) flows when the diode is reverse biased. As the reverse bias is increased, the curve begins to bend sharply toward the vertical. This is the breakdown region. Rectifying diodes cannot operate here, but special diodes, called *zeners*, can. For most applications, the diode can be considered as a switch that closes when the voltage across it is zero in the forward-bias direction and opens when the voltage across it is less than zero (reverse bias).

DIODE APPLICATIONS

Rectification

The diode can be used to convert ac to dc. This action, called *rectification,* exploits the fact that the diode conducts most readily in one direction only. Figure 10-13 shows a half-wave rectifier, and Figures 10-14 and 10-15 show that

the diode conducts only on the positive half-cycles and transforms the ac wave into a unidirectional pulsating dc. For most applications, the output of Figure 10-15 must be smoothed (filtered). A relatively large capacitor placed across the load can accomplish this (Figure 10-16). On each positive half-cycle, the capacitor will be charged to the peak value of the voltage across the transformer secondary. When the supply voltage decreases, the diode will turn off, and the capacitor will discharge into the load. If the circuit values are correctly chosen, the much smoother output of Figure 10-17 will be obtained.

Full-wave rectification provides a smoother output than does half-wave rectification. Figures 10-18 and 10-19 show that the center-tapped, full-wave rectifier is essentially two half-wave rectifiers working into the same load. The upper diode, D_1, conducts on the positive half-cycle, and D_2 conducts on the negative half-cycle. Both send current through the load in the same direction, producing the output shown in Figure 10-20. The pulsations in this wave occur at twice the frequency of the half-wave rectifier. A capacitor placed across the load (Figure 10-21), is charged twice as often, giving the smoother output shown in Figure 10-20b.

Figure 10-22a shows a full-wave bridge rectifier. On the positive half-cycle, electron current flows from $B-$ through D_2, the load, D_3, and back to $A+$. On the negative half-cycle, electron current flows from $A+$ through D_1, the load, D_4, and back to $B-$. In both cases the current flows through the load in the same direction. The bridge rectifier uses the full output of the transformer and does not require a center-tapped transformer. However, four diodes are required, and the total volt-drop across the diodes is twice that of the full-wave rectifier of Figure 10-18. Figure 10-22b is another representation of Figure 10-22a.

Zener Diodes

The zener diode is used whenever a constant voltage is required. Figure 10-23 shows its circuit symbols, and Figure 10-24 displays a typical characteristic. This shows the voltage across the diode versus the current through it. When operated beyond the zener breakdown point, this characteristic becomes an almost vertical line. This means that in this region, the voltage across the zener is almost constant and independent of current. A load placed across the zener (Figure 10-25) shares this constant voltage. R_1 in Figure 10-25 limits the zener current and restricts its operation to the zener region.

TRANSISTORS

The transistor is a three-terminal, solid-state device that provides current, voltage, and power amplification. Typical body shapes are shown in Figure 10-26. The three transistor terminals attach to the emitter, base, and collector. In an NPN transistor, the base is an extremely thin, P-type slab sandwiched between

two N-type slabs (Figure 10-27). In a PNP, the base is N-type, and the emitter and collector are P-type (Figure 10-28). Figure 10-29 shows the circuit symbols of the transistor. The arrow on the emitter indicates the direction of the positive current flow (opposite to the electron flow) when the base-emitter circuit is forward biased.

Transistor amplification is illustrated in Figure 10-30. Figure 10-30a shows an NPN transistor with the emitter grounded, the base connected either to the ground or to a positive voltage, and the emitter positive. Figure 10-30b shows the potential distribution from emitter to collector. This transistor may be viewed as two joined diodes (Figure 10-31). Diode 1 comprises the emitter and base, and diode 2 comprises the base and the collector.

With its base grounded, diode 1 is forward biased, but not completely, as a residual voltage opposes the current flow. The depletion region of this diode lies between *c* and *d* in the diagram. The upward sloping line between emitter and base shows that internally the emitter is slightly more positive than the base. (Upward motion means moving from positive to negative.) Free electrons are the carriers of current in the emitter. When the base is made more positive, the potential hill is lowered, and electrons enter the base. Only electrons above the hill have sufficient energy to enter the base and create current. As the hill is raised or lowered by a signal applied to it, fewer or greater number of electrons can surmount the hill. Therefore the base current mimics the base signal.

Diode 2 is strongly forward biased from base to collector (reverse biased from collector to base). This is shown by the long fall from *e* and *d*. Electrons that are able to leave the emitter and enter the collector will gain energy by falling through this voltage change. Because the base is always very thin, 98 percent or more of the electrons entering the base will pass through it, enter the collector, and descend the base collector slope. As a result, small current changes controlled by a weak signal at the base will generate large current changes out of the collector. The transistor therefore functions as a current amplifier.

The PNP transistor acts in exactly the same way except that all voltages and currents are reversed.

Transistor-Circuit Configurations

The three possible circuit configurations of transistor amplifiers are shown in Figure 10-32. Each configuration has its own function. The common base (CB) provides voltage and power gain but no current gain. It has a low input impedance and a high output impedance. Consequently, it is often used for matching a low impedance source to a device requiring a high input impedance. The common emitter (CE) provides current, voltage, and power gain and it is widely used as an amplifier. The common collector (CC) provides current and power gain. It has a high input impedance and a low output impedance and is widely used to match devices. For all configurations, R_1 limits the emitter-base current, and the output is taken across R_2.

THE SILICON-CONTROLLED RECTIFIER

The silicon-controlled rectifier (SCR) is a solid-state electronic switch. It is primarily and widely used to control high power and large currents. The circuit symbol, typical appearance, and structure are shown in Figure 10-33. The SCR is a three-terminal diode with anode, gate, and cathode terminals. The gate is connected to the P region adjacent to the cathode (cathode gate). This is the most sensitive position. In use, the anode-cathode circuit is placed in series with the load and the power source and adjusted so that it will not turn on in the absence of a voltage pulse across the gate-cathode circuit. By controlling the timing of this pulse, the power delivered to the load can be controlled. Extensive development to meet the needs of industry has produced SCRs with current handling capacities from 0.5 to 2,500 amps, operating at voltages up to 3,600 volts. These are used to control motors of all sizes and to rectify and control heavy power.

Operating Characteristics

Figure 10-34 shows the operating characteristics of the SCR. Figure 10-34a shows the SCR with zero volts from gate to cathode. In this state there is a critical voltage called the *forward breakover voltage*. Below this voltage, a small leakage current *(forward blocking current)* flows. At this voltage, the SCR turns on abruptly and acts as a closed switch. It will not turn off until its current is reduced below a level called the *holding current*. A reverse voltage below the reverse breakdown voltage will produce a small reverse leakage current. A reverse voltage at or above the reverse breakdown voltage will damage the SCR.

Figure 10-34b shows that the SCR's breakover voltage is reduced by the gate current. At a sufficiently high gate current, the entire blocking region is removed, and the SCR behaves like a conventional diode. Reducing the gate current will not turn off the SCR; however, it remains on (latched) until its anode current is reduced below the holding current level. In practice, the SCR is turned on by a brief, voltage pulse, which permits precise turn-on timing.

SCR Operation

The SCR's four-layer, three-junction structure can be analyzed into the two-transistor model of Figure 10-35 and the circuit of Figure 10-36. The circuit contains a PNP and an NPN transistor. The PNP conducts when its base-emitter voltage is negative, and the NPN conducts when its base-emitter voltage is positive.

Assume that a positive pulse is applied to the base of the NPN transistor. The base-emitter circuit is now forward biased; the NPN transistor begins to turn on; and the collector current increases. The collector voltage drops. Because the PNP base is tied to the NPN collector and the PNP emitter is at the anode voltage, the PNP base emitter becomes lightly forward biased. This in turn increases the NPN collector current which produces more forward bias in the PNP. A regenerative

feedback action ensues, ending with both transistors fully on. Removing the initial gate pulse will have no effect because the PNP collector current will flow into the NPN gate and keep it on. The circuit can be turned off by reducing the PNP current to a value at which the NPN begins to turn off. The regenerative feedback action then proceeds in reverse.

THE TRIAC

The triac is a three-terminal, semiconductor, bilateral switch. It operates very much like two SCRs connected in parallel with one reversed, and therefore it can be turned on by a gate pulse for both positive and negative anode voltages. At present, triacs are available in current ratings up to 40 amps and for voltages up to 600. Figure 10-37 shows the structure of a triac, and Figure 10-38 shows its ac characteristic. The triac is used to control and deliver ac power. It has application, therefore, in the full-wave control of universal motors and for the control of induction motors. Because time is required to turn it off between positive and negative cycles, the triac is limited to an upper operating frequency of about 400 Hz.

TRIGGERING THE SCR AND THE TRIAC

SCRs are often triggered by lower-powered solid-state devices that can be more easily and more precisely controlled. These devices, classified as *triggers*, include the unijunction transistor (UJT), the programmable unijunction transistor (PUT), and the silicon unilateral switch (SUS). The triac is often triggered by the diac, which is discussed on page 275.

Unijunction (UJT)

The UJT is a three-terminal, single P-N junction device that can function as a latching switch. Its structure, symbol, and appearance are shown in Figure 10-39. It consists of an N bar (N-type material) with a single P-type region on one side of the bar about halfway down. The upper and lower ends of the N bar are designated B_2 and B_1, respectively. The P region is called the emitter *(E)*.

The UJT operates like a simple resistor when the emitter is grounded and a positive voltage is applied across B_2–B_1. However, when the emitter voltage is raised to the UJT's firing voltage (V_F), the resistance of the E–B_1, circuit abruptly drops to a low level. This action is illustrated in Figure 10-40. A voltage across B_2–B_1, sends current through the N bar, producing a resistive voltage drop (Figure 10-40). The voltage adjacent to the P insert is raised as a result. As long as the P-N junction is back biased, the resistance from emitter to B_1, is relatively large (two to six kilohms). When the emitter voltage becomes slightly

higher than the adjacent N region, carriers (holes) are injected into the N bar. This current flow reduces the resistance between E and B_1. The forward bias is further increased, and more current flows, further reducing the resistance of the E–B_1 path. A regenerative flyaway action follows. This action ends when the emitter current reaches a peak value determined by other elements in its circuit. The UJT is now turned on. Removing the initial emitter voltage has no effect, as a high current flows in the E–B_1 circuit. The UJT can be turned off only by reducing that current and returning the P-N junction to its reversed bias state.

Figure 10-41 shows a UJT relaxation oscillator circuit. This circuit is frequently used to turn on (*fire*) an SCR. The SCR gate-cathode circuit is connected across R_3. When the switch is open, the voltage across C_1, is low, and the UJT and SCR are off. Closing the switch causes the voltage across C_1 to rise at a rate determined by the supply voltage and R_1. When the UJT firing voltage is reached, the UJT turns on, and C_1 discharges through R_3, producing a pulse large enough to fire the SCR.

The Programmable Unijunction Transistor (PUT)

The PUT is used whenever an SCR requires a higher voltage pulse than that generated by a UJT. The PUT is a four-layer, three-terminal device with an anode, cathode, and an anode gate (gate is connected to the region adjacent to the anode). It resembles an SCR but is lower powered and has a different internal structure. Figure 10-42 shows its circuit symbol and a PUT relaxation oscillator.

The PUT fires when its anode voltage exceeds the gate voltage by 0.5 to 0.7 volts. The gate voltage is set by R_1 and R_2. Therefore the anode-firing voltages can be controlled or programmed. The on-resistance of the PUT is much lower than that of the UJT. It can discharge a capacitor more rapidly and completely and give higher pulse currents and voltages than the UJT can. Therefore it can drive higher-powered SCRs.

The Silicon Unilateral Switch (SUS)

The SUS is a four-layer diode with an anode gate. The SUS is turned on when the anode voltage reaches a critical voltage called the *switching voltage* (V_s). The anode gate is much less sensitive than a cathode gate is and is usually used for synchronization. When turned on, the SUS acts as a latching switch similar to the UJT and PUT. The SUS has a higher switching current and voltage than the UJT. Figure 10-43 shows the circuit symbol, equivalent circuit, and the characteristic. The characteristic is similar to the SCRs with zero gate current, but the current scale is smaller.

The Diac

The diac (bilateral trigger diode) is a five-layer, two-terminal device. It can be viewed as two, four-layer diodes connected in inverse parallel. Lacking a gate,

the diac can be fired only by positive and negative anode voltages. Diacs are designed to trigger any well-designed triac circuit. Figure 10-44 shows the circuit symbol and characteristic of a diac.

SOLID-STATE PHASE CONTROL

Phase-control circuits deliver only a portion of the ac supply to a load. They accomplish this by controlling the *on-time* of an SCR (or triac) in series with the load. Figure 10-45 shows a half-wave phase control using an SCR. If the trigger pulse fires the SCR at the beginning of each positive half-cycle, then the shaded waveform shown in Figure 10-46 will be delivered to the load. This is half of the available supply power. If the trigger pulse fires the SCR at exactly 90° into the positive half-cycle, then the shaded waveform of Figure 10-47 (one-quarter supply power) will be delivered to the load. Motors that respond to supply power reduction with decreasing speed can be controlled by this circuit.

Half-wave Phase Control

The waveforms of Figures 10-46 and 10-47 illustrate half-wave phase control. The maximum supply power available to the load is one-half the ac supply power. Half-wave control is used for motors that can operate from these pulsating dc supplies and change speed as supply power varies. Control ranges from zero to one-half of the maximum supply power.

Full-wave Phase Control, DC and AC

Full-wave dc control is obtained by full-wave rectifying the supply voltage. Each half-cycle becomes positive-going. The SCR can then supply the maximum to one-half the maximum supply power to the load. Figure 10-48 shows a bridge rectifier supplying power to an SCR-controlled motor. This is a simplified circuit that omits necessary refinements. Figure 10-49 shows the waveform delivered to the motor.

Full-wave ac control is illustrated in Figure 10-50a, b, and c. Control ranges from maximum to one-half maximum, and the waveform delivered to the load contains no dc. In Figure 10-50a, SCR_1 acts as a controlled half-wave rectifier for the positive half-cycle. SCR_2 does the same for the negative half-cycle. The bridge rectifier in Figure 10-50b causes the SCR to conduct on both positive and negative half-cycles, and therefore controlled ac is supplied to the load. Figure 10-50c replaces the two SCRs of Figure 10-50a with a triac. This is the recommended circuit.

Trigger Circuits

SCRs (and triacs) can be directly or indirectly triggered by two basic circuits: resistance and resistance-capacitor (RC) triggers. Direct triggers feed to the

SCR's gate. Indirect triggers fire trigger devices that in turn fire SCRs. Both methods use similar circuits, but indirect triggering is more precise.

Direct resistance triggering is illustrated in Figure 10-51. During the positive half-cycle of the supply with S_1 closed, the SCR's anode and gate voltages rise in step. Figure 10-36 shows the gate-cathode circuit to be similar to the base-emitter circuit of a transistor. Therefore, the gate-cathode voltage is low, and the load current is limited by the SCR's anode voltage. When the current in the gate reaches the critical level, it will fire the SCR. The SCR's anode voltage then drops abruptly and the load current increases. The gate current also drops. During the negative half-cycle the SCR turns off. The gate-cathode circuit is protected by D_1 from excess negative voltage during this cycle. The magnitude of R_1 controls the SCR's firing angle. Firing angles from zero to 90°C can be obtained.

Indirect *RC* triggering is illustrated in Figures 10-52 and 10-53. The trigger voltage in both cases is the result of current flowing through R_1 and charging C_1. Until the UJT fires, its emitter circuit can be considered an open circuit. Therefore the voltage across C (V_C) depends only on R_1, C_1, and the voltage across the *RC* branch. The time *(T)* required to charge the capacitor to 63.2 percent of the branch voltage is

$$T_{\text{charge}} \text{ (seconds)} = R_1 \text{ (ohms)} \times C_1 \text{ (farads)}$$

Similarly, the time *(T)* required to discharge the capacitor to 36.8 percent of its maximum voltage is

$$T_{\text{discharge}} \text{ (seconds)} = R' \text{ (ohms)} \times C_1 \text{ (farads)}$$

where R' equals the resistance in the capacitor's discharge path (the emitter-B_1 circuit and R_2 in Figures 10-52 and 10-53). R' is made as small as possible to give a brief high current pulse to trigger the SCR. R_1 is usually made variable. The time in the positive half-cycle when V_C reaches the UJT's firing voltage can then be controlled. Firing angles from zero to 180° can be obtained. Figure 10-52 uses a half-wave dc supply, and Figure 10-53 uses a full-wave ac supply.

Figure 10-54 shows a circuit with R_1 replaced by a PNP transistor (Q_1) in series with R_3. The current through Q_1 is the capacitor-charging current. This current is controlled by the current into the base of Q_1. This permits sophisticated electronic feedback control (discussed later). A full-wave dc supply is required for reliable transistor operation.

Figure 10-55 shows a transistor-controlled UJT pulse circuit that corrects a deficiency in Figure 10-54. In the former circuit, the voltage across the transistor and the UJT depends on the SCR's state. It is highest when the SCR is off and lowest when the SCR is on. This complicates control. In Figure 10-55 a zener diode voltage regulator is used to stabilize this voltage. As long as zener current is sufficient to keep it on, its voltage remains constant. The zener voltage also supplies the transistor and the UJT.

PHASE CONTROL OF MOTOR SPEED

Electronic phase control is used to control motor speed, to start and stop motors, to reverse rotation, to provide overload protection, to provide braking, and to limit starting current. Here we shall concentrate on speed control.

It is always risky to operate a device outside its ratings for the following reasons: (1) Doing so generally nullifies all of the manufacturer's guarantees. (2) Most motors are rated for operation at a single speed, and at lower speeds their cooling means may be inadequate. The lubrication of their bearings may also be inadequate at lower-than-rated speeds. (3) Motors designed to work on pure ac may respond erratically to the phase-control waveform. Finally, (4) Phase control of motor speed may depend on motor characteristics not guaranteed by the vendor.

For example, some controls for a universal series motor depend on a residual magnetism in its magnetic structures. This residual magnetism is unwanted in normal operation, and so the manufacturer may well be working to eliminate this characteristic. Potential problems of this type can be avoided by consulting the motor vendor beforehand when an unorthodox use is anticipated.

Reference and Feedback Signals

A circuit using feedback to govern a motor's speed must, in some way, sense the motor speed. In brush-type motors, the back e.m.f. generated by the motor while the controlling SCR is off provides a good indication of motor speed. For separately excited shunt-field–wound and permanent-magnet field motors, this e.m.f. is proportional to the field. However, the field of a series-wound motor is not energized when the controlling SCR is off. Residual magnetism must be used to gauge motor speed. Residual magnetism also depends on past current as well as motor speed and is not, therefore, strictly reliable.

Feedback motor controls usually compare the fedback voltage with a reference voltage. Motor speed is changed until the difference between the two voltages is less than some specified amount. Figure 10-56 shows a circuit in which a reference and feedback voltage are compared. The difference ($V_{\text{REF}}-V_{C\ \text{EMF}}$) is the SCR's gate-cathode voltage. Figure 10-56 illustrates this effect using two voltage sources. For $V_{\text{REF}} = 20\ V$ and $V_{\text{FEEDBACK}} = 15\ V$, $5\ V$ appears across the load (input of the firing device).

UNIVERSAL SERIES MOTOR CONTROL

The Universal series motor is a brush-type motor. Therefore the back e.m.f. generated during the SCR off-cycle can be used to measure motor speed. This e.m.f. depends on the residual magnetism of the field poles, and consequently the precautions noted previously should be observed.

Half-wave Control with Feedback*

Figure 10-57a shows a half-wave feedback circuit advanced by Momberg and Taylor.† In this circuit the SCR is inserted between the field winding and the armature. The SCR cathode is therefore lifted above the ground by the armature voltage. The reference voltage (V_G) is derived from a potentiometer connected across the ac line. The reference voltage is an attenuated sine wave in phase with the anode voltage of the blocked SCR. When the motor is stationary, the armature voltage is zero, and the SCR's gate current is maximum. Therefore the SCR fires early in the cycle, providing maximum power to the motor. As the motor speed increases, a voltage proportional to speed develops across the armature. The SCR's gate-cathode voltage is consequently reduced, thus decreasing the gate current (SCR off) and delaying the firing time. Less power is delivered to the motor, allowing it to smoothly slow down to a stable speed.

An increase in load tends to reduce the motor speed. The armature voltage will decrease; the SCR's gate current will increase; and the firing angle will be advanced. More power will be delivered to the motor, restoring its speed. The motor will then stabilize at a speed reflecting an equilibrium among the armature voltage, the gate current, and the motor power. Essentially the motor will maintain a fixed speed over a range of loads. The specific speed depends on the position of the potentiometer arm.

Figure 10-57b shows the circuit waveforms when V_G is relatively high. The SCR is fired early in the cycle, and the motor runs at a high speed. Figure 10-57c illustrates the case for a lower V_G. The firing is delayed, and the motor runs at a lower constant speed.

The circuit has some disadvantages. The total resistance in the R_1P_1 branch must be low enough to provide sufficient gate current to trigger the SCR. Therefore the branch may dissipate considerable energy. The SCR cannot be fired at angles greater than 90° (one-quarter-cycle operation). At low speeds, the motor may need less than one-quarter cycle to reach a stable speed. The SCR may not fire for several cycles, which causes a hunting or "cogging" effect accompanied by an objectionable mechanical noise.

Figure 10-58 shows a half-wave control circuit that permits a stable low-speed operation by allowing less than a one-quarter-cycle conduction. The key elements are the zener diode (CR_3) and capacitor C_1. The zener diode clips the supply voltage at a low level. The voltage across it is practically constant for the entire positive half-cycle. C_1 therefore charges at an almost constant rate throughout the positive half-cycle. During the negative half-cycle, the zener is forward biased at virtually zero volts. C_1 discharge to almost zero.

The charging rate depends on the P_1 setting and the value of C_1. With a proper choice of C_1 and P_1, the SCR can be made to fire anywhere from zero to 180°.

*Adapted from General Electric Co., Semiconductor Products Dept.

†U.S. Patent No. 2,939,064, J. W. Momberg et al., "Motor Control Systems," May 31, 1960, assigned to the Singer Manufacturing Co.

Figure 10-58d shows the zener voltage. Figure 10-58b shows the motor voltage and the voltage across C_1 (V_{C1}) at high speed, and Figure 10-58c shows the slow-speed case. Feedback control operates as in Figure 10-57.

The other circuit components act to protect and stabilize the circuit. If C_1 does not discharge to exactly the same level in each cycle, the SCR's firing will be erratic. CR_2 provides a low resistance path to discharge C_1. CR_1 permits C_1 to fire the SCR during the positive half-cycle but protects the SCR's gate from excessive negative voltage during the negative half-cycle. The one-kilohm resistance and C_2 bypass the commutator hash and extraneous signals that can fire the SCR prematurely.

Both circuits (Figures 10-57 and 10-58) require separating the motor's field and armature. This is necessary to keep the feedback uncontaminated by the voltage induced in the field by the rotating armature. If the field were not separated, a small voltage would be induced in it by transformer action. This would modify the feedback signal. In both circuits these slight changes in the level of the firing voltage cause unacceptable shifts in firing time. This is a result of the flat gate voltage of Figure 10-56 and the slowly rising gate voltage of Figure 10-57. Figure 10-59 shows how steeper SCR gate-cathode voltage slopes improve firing stability: a and b show the decreased time shift (Δt) for linear voltages equally displaced, and c shows the effect for a phase-shifted sine wave.

The circuit of Figure 10-60a reduces the SCR's sensitivity to gate-cathode voltage changes by increasing the steepness of the gate-cathode voltage waveform. The SCR is fired by a steeply rising sine-wave gate signal instead of by a flat or slowly rising one. The motor speed is controlled by shifting the phase of this sine wave, as in Figure 10-60b and c. This eliminates the need for separate field and armature connections.

The circuit operates as follows: During the positive half-cycle, CR_2 turns on, developing a small constant reference voltage at its anode (top). A sine-wave voltage in phase with the supply is developed between the P_1 and the anode of CR_2. C_1 shifts the phase of this voltage. This sine wave sits on the diode reference pedestal. Both the phase shift and amplitude of the SCR's gate voltage depend on the position of the P_1 arm and the value of C_1. When these are properly chosen, almost 180° control is obtained. CR_1 and R_2 serve the same function as in Figure 10-58. Different-sized motors require different component values (Figure 10-60d). Sometimes the motor hunts when P_1 is at minimum setting, though this depends on the minimum resistance of P_1. However, a small trimpot added between P_1 and CR_2 can be adjusted to eliminate this hunting.

The R_1–P_1 resistance in Figure 10-60 must be low enough to deliver the required gate current to the SCR. At low-speed operation, firing occurs when the instantaneous value of the supply voltage is low. Therefore R_1, P_1 must be small and may be required to furnish high currents and dissipate high wattages. In many cases the required wattages are impractical. The circuit of Figure 10-61 eliminates this problem by interposing an SUS between the SCR's gate and the

R_1, P_1 circuit. The SUS fires when its breakover voltage (eight to ten volts) is exceeded. It then acts as a very low resistance, rapidly discharging C_1 and delivering a strong pulse to the SCR gate. The R_1, P_1 network is independent of the SCR's gate-current requirements. High-value, low-wattage resistors can be used.

Using a PUT as a trigger device also acts to isolate the SCR gate from the R_1, P_1 circuit. In addition it offers additional advantages over the SUS. Design is made more flexible and operation more precise, as the breakover voltage is adjustable. Also, the PUT can trigger higher-powered SCRs than the SUS can.

Figure 10-62 shows a PUT-triggered control circuit. The section of the figure outside the dashed box is similar to the SUS circuit. However, the circuit within the box is different. The PUT's breakover voltage depends on its gate voltage. This voltage is derived from a voltage-regulated source (the zener diode D_1) divided by R_6 and R_7. R_4 and R_5 form the adjustable pedestal on which the trigger ramp sits. R_2 and R_3 control the charging rate of C_1.

The system operates as follows: At the beginning of each positive half-cycle of the supply voltage, the voltage across the zener rises until it turns on at 22 volts. C_2 is charged through R_6 and R_7 to the zener voltage, which is also the PUT's gate voltage. At the same time, C_1 is charging through R_2 and R_3, starting from a pedestal voltage determined by R_4 and R_5. The PUT will fire when its anode voltage (V_{C1}) exceeds its gate voltage by 0.5 to 0.7 volts. When the back e.m.f. is greater than V_{C2}, V_{C2} will remain at 22 volts. When the back e.m.f. is less than V_{C2}, D_3 will conduct and clamp V_{C2} at the back e.m.f. This will decrease the PUT's gate voltage, and if the PUT's anode voltage is high enough, it will fire and trigger the SCR through pulse transformer T_1. Whenever the back e.m.f. becomes greater than 22 volts, D_3 will turn off. The PUT's gate voltage will rise to 22 volts, delaying firing. Adjusting the speed control (R_5) raises and lowers the starting voltage of the C_1 charging ramp.

Full-wave Universal AC Series Motor Control*

Diacs and triacs are well suited for full-wave motor control. Figure 10-63 shows a basic full-wave ac control without feedback. C_1 is alternately charged positive and negative through R_1, P_1 by the supply voltage. When V_{C1} reaches the diac's breakover voltage (positive or negative), the diac fires, generating a pulse that fires the triac. The phase angle at which the firing takes place is controlled by the R_1, P_1, C_1 circuit. Control for this circuit ranges from zero to 90° for both positive and negative cycles.

Triacs require a short interval to turn off (commutate) when their anode voltages are reversed. To maintain control for both positive and negative cycles, the triac must turn off whenever its anode voltage reverses. An abrupt current turn-off in a circuit containing an inductance (motor field) generates a high rapidly changing voltage spike of opposite polarity to the supply voltage. If this spike

*Adapted from General Electric Co., Semiconductor Products Dept.

rises too rapidly (rapid *dv/dt*), the triac will be unable to commutate, and control will be lost for the next half-cycle. The R_2, C_2 circuit retards the *dv/dt* of the spike by attenuating high-frequency components so that the triac can turn off and retain control.

Full-wave DC Control with Feedback*

Figure 10-64 shows a full-wave dc control circuit with feedback. This circuit requires separate field and armature connections. The full-wave bridge converts the ac supply to periodic positive half-cycles. The position of the P_1 arm determines the SCR's firing angle. *CR*6 is a free-wheeling diode used to maintain field current when the SCR is off. Circuit operation is similar to that of Figure 10-57.

The circuit has several disadvantages: Its firing angle ranges from zero to 90°. R_1, P_1 must supply gate current to the SCR. Also, because the SCR's anode voltage does not reverse, at low speeds the back e.m.f. may be insufficient to turn off the SCR. This can cause hunting.

Full-wave Control with Precise Triggering

All phase-control circuits triggered directly or indirectly by a charging capacitor face the same problem. Unless the capacitor discharges to the same level each time that the SCR is fired, the timing will be erratic and possibly troublesome. Figure 10-65 shows a full-wave UJT control circuit that corrects this problem. The UJT fires whenever its emitter voltage is 0.7 volts higher than the adjacent N-bar voltage. This voltage depends on the B_2 voltage. At the end of each half-cycle V_B2 is zero. Therefore the UJT acts like a diode and clamps V_{C1} to 0.7 volts. The maximum voltage across C_1 is also held constant by the zener diode. Therefore the C_1 waveform is duplicated each half-cycle. Within the cycle, the UJT will fire in the normal way and trigger the SCR.

SHUNT OR P-M FIELD MOTOR CONTROL

The shunt-wound dc (or permanent-magnet field) motor readily adapts to solid-state speed-control circuits. Its speed is controlled by the voltage across its armature and remains approximately constant despite changes in torque. If required, its speed can be made virtually independent of the torque by adding a small compound-series winding or introducing feedback into the armature voltage supply.*

*Adapted from General Electric Co., Semiconductor Products Dept.

Half-wave Control without Feedback

Figure 10-66 shows a simplified half-wave control circuit without feedback. During the positive half-cycle, C_1 supplies a phase-shifted voltage to the trigger device. The triggering time is controlled by P_1. The trigger device may be a diac, SUS, UJT, or other. The shunt field is energized through D_1 while L_1–L_2 is negative (solid arrows). During the next half-cycle, D_1 cuts off, but the inductive field of the field coil collapses slowly. This action maintains a current circulating through the field coil and D_1 in the desired direction (dotted arrows). D_1 is called a *back* or *free-wheeling rectifier*. The armature in series with the charging circuit has an insignificant effect on the phase of V_{C1}, and therefore the circuit provides no feedback.

Half-wave Control with Precise Triggering and Feedback*

Shunt motors are often designed for half-wave operation from a 117-volt, ac supply. They can be precisely controlled by the circuit of Figure 10-67. In this circuit, C_1 is charged through the motor armature and D_4, while the SCR is off. This arrangement provides the feedback required for constant speed. If the motor slows down, its back e.m.f. will decrease, and C_1 will reach the firing voltage sooner. This speeds up the motor. If the motor speeds up, its back e.m.f. will increase, and the charging current into C_1 will decrease. This delays the SCR's firing point and returns the motor to its previous speed.

Precise triggering is obtained by discharging C_1 through D_2 and the motor field during each negative half-cycle. During this period, both D_3 and D_2 are on. Therefore C_1 discharges to 1.4 volts and begins to charge from this voltage at the start of the next positive cycle. The firing time is adjusted by R_1. A diac triggers the SCR, but an SUS, UJT, or PUT can be used as well.

Using a Neon-Bulb Trigger*

Neon bulbs can also be used as triggers. They have characteristics similar to diacs, with switching voltages about 90 volts and switching currents below 1 μA. However, their switching time is long compared with that of solid-state devices. Their only advantage is their low cost. Figure 10-68 shows a simple, low-cost, half-wave motor control using a neon bulb. An ac voltage appears across C_1. Therefore V_C is a phase-shifted voltage rather than a capacitor-charging voltage. The neon bulb is triggered by both positive and negative half-cycles, but the SCR responds only to the positive ones. Although the armature is in series with R_1, P_1, and C_1, feedback is not provided because the armature's back e.m.f. has little effect on the phase of V_1. The dotted box shows the circuit for a dc shunt motor. The circuit also works for a series-field universal motor, as shown.

*Adapted from General Electric Co., Semiconductor Products Dept.

Full-wave Speed Controls for Shunt Motors*

Figure 10-69 shows a simple yet excellent full-wave speed control for dc shunt motors. This circuit embodies both precision firing and feedback.

Precision firing is accomplished at the end of each half-cycle, by triggering the SUS. Normally the SUS is triggered when the anode to cathode voltage is between six to eight volts. However, it also triggers when the gate voltage is much lower than the anode. At the end of each half-cycle, the gate voltage falls to zero (R_1, R_2 voltage divider). This discharges C_1 completely.

Feedback occurs in two ways. V_{C1} depends on the armature's back e.m.f. At high speeds, this is high and reduces the C_1 charging current. At low speeds, the opposite effect takes place. Also, collapsing energy stored in the armature's inductive field will keep D_3 on for a short time at the start of each half-cycle. When D_3 is on, the armature is shorted, and its back e.m.f. cannot affect V_{C1}. The C_1 charging rate is increased. Armature current increases with torque. Therefore higher torque will keep D_3 on longer and decrease the firing angle.

Otherwise, circuit operation is similar to that of other full-wave control circuits. The bridge rectifier converts ac to periodic positive half-cycles. The SUS fires when V_{C1} reaches six to eight volts. R_3 controls the charging rate of C_1 and, consequently, motor speed.

Full-wave, single-SCR motor controls often face a turnoff problem. After each positive half-cycle, the SCR must turn off to regain control in the next cycle. Under full-wave drive, the turnoff time may be insufficient for this to happen.

Figure 10-70 shows a full-wave motor-control circuit that solves this potential problem. Here SCR_1 and SCR_2 conduct on alternate half-cycles, although they are triggered by the same circuit. With A−, electron current flows through D_1, through the armature, through SCR_2 (when it fires), and returns to B. SCR_1 is off during this period. With B−, electron current flows through D_2, through the armature, through SCR_1 (when fired), and returns to A. Current flows through D_1, the field, and D_4 with A−. With B−, current flows through D_2, the field, and D_3. The direction of current flow is the same in both cases.*

The circuit of Figure 10-70 is also economical. D_3 and D_4 carry only field current, and therefore they can be small lead-mounted diodes without heat sinks. Each SCR carries half the total armature current. They can therefore be smaller than the SCR in an equivalent single SCR circuit. This simplifies heat sinking.

INDUCTION MOTOR CONTROLS*

Induction motor speeds are not easily controlled by phase-control circuits. These motors are primarily frequency sensitive, and consequently they respond more readily to variable-frequency drives than to voltage control. Much depends on the motor's specific characteristics, but in general, when phase control is used, motors should be as voltage sensitive as possible. The variable-voltage drive of

*Adapted from General Electric Co., Semiconductor Products Dept.

induction motors is a compromise usually dictated by economics, though control can be satisfactory when properly implemented.

Split-phase and capacitor-start induction motors require a switched start winding to supply the starting torque. Motor speed cannot be controlled until the start winding is switched out, and so the switching point must be lower than the speed-controlled speed range.

Figure 10-71 shows how the voltage (phase) control of induction motors depends on their speed-torque characteristics. Curves showing the speed-torque characteristics of a fan and those of a low rotor-resistance, permanent-split capacitor motor are shown. The motor characteristics are shown at two supply voltages. The motor speed in each case is given by the intersection of the fan and motor characteristic. Figure 10-71a shows very little speed variation in supply voltage, and Figure 10-71b illustrates the case for a high rotor resistance. Here the speed variation with supply voltage is greater.

Information on the speed of the induction motor cannot be derived from any inherent motor parameter, and so it is usually necessary to use a small tachometer generator for this purpose. The tachometer's output does not have to be precise, but it should be repeatable. Sometimes speed information can be indirectly derived. For example, in a furnace-blower system, the air temperature can be used to measure the blower speed. Figure 10-72 shows a furnace-blower control. The air temperature controls the resistance of thermistor R_3 which controls the triac's firing angle.

Figure 10-73 shows a block diagram of an induction motor's speed control using a tachometer. The tachometer's voltage output is compared with a reference voltage. The result is used to control the motor speed. A negative output (reference voltage lower than the tachometer's) will decrease the motor speed. A positive result (reference voltage higher than the tachometer's) will increase the motor speed. Motor speeds are set by adjusting the reference voltage.

Figure 10-74 shows a practical induction motor's speed control. The tachometer generates an ac voltage proportional to the motor speed. Each time the ac tachometer's output swings positive, C_1 and C_2 are charged. On the negative swing, C_1 is discharged. The speed-control potentiometer controls the discharge of C_2. V_{C2} is filtered by the ten-kilohm resistance and the 5 μF capacitor. The dc voltage generated is the feedback signal. The integrated circuit (IC), PA436, is a sophisticated solid-state phase-control package that delivers a trigger pulse. The timing of this pulse depends on the difference between V_{C1} and the filtered V_{C2}. The motor speed is adjusted until this difference is very small. (The PA436 has now been replaced by more advanced packages.)

SCR PROTECTION*

SCRs must be protected against excessive negative anode-cathode voltages, or they will break down. Figure 10-75 illustrates a protection scheme using diodes,

*Courtesy of Square D Co.

fuses, and surge protectors. Diode 3 Rec limits reverse SCR voltage to about 0.7 volts, the diode *on* voltage. Diode 2 Rec blocks the negative half of the supply voltage. The two diodes keep the SCR's reverse voltage to a low and safe value. The fuse (1FU) and the surge protector (1SP) protect the SCR from excessive currents. The fuse provides protection from prolonged current overloads. The surge protector, a low resistance for normal currents, becomes a very high resistance when large current transients are present.

USING TRANSISTORS IN MOTOR-CONTROL CIRCUITS

Transistors can be used to increase the sensitivity and enhance the control of trigger circuits. They are used to amplify the error signal in feedback circuits, provide constant current sources for charging capacitors, and discharge trigger capacitors for precise timing.

Figure 10-76 illustrates the use of the transistor as an amplifier and a constant current source. Here the current into the base of Q_2 consists of an electron flow through R_1 from right to left, due to the setting of P_1, and an electron flow from left to right, due to feedback. Therefore the base current depends on the difference between the reference and the feedback voltages. This error signal controls the amplified and reversed emitter-collector current that charges C_2. Thus the sensitivity of the control circuit is considerably increased. Also the emitter-collector current is independent of the emitter-collector voltage and depends only on the base current. Therefore a constant-error, negative base current will charge C_1 with a constant, amplified, positive emitter-collector current. This will generate a straight-line ramp voltage across C_1 rather than the flattening exponential curve produced by conventional charging circuits. The straight-line ramp results in more precise firing.

The circuit operates as follows: When the motor speed corresponds to the setting of P_1, the error signal is small and negative. This will become more negative if the motor speed decreases. The base electron current increases, and the emitter-collector current increases in the opposite direction. This charges C_1 more rapidly and increases the motor speed. The reverse occurs if the motor speeds up. A dc supply voltage is required for the transistor, which is provided by the half-wave rectifier D_1 and is filtered by C_1. The full-wave dc supply (Figure 10-77) will provide a more constant dc and improve performance.

Figure 10-78 shows how a transistor is used to discharge the trigger capacitor for precise triggering. Q_3 parallels C_2. Whenever Q_3 is fully turned on, C_2 will discharge completely through Q_3. Q_3 can be turned on by a surge of positive base current. When the ac supply voltage is not close to zero, current flows through either D_1 or D_2, through D_3, and through R_6. D_3 is kept on. Current from R_4 flows through D_3, and Q_3 is kept off. At the beginning and end of each positive cycle, the ac supply voltage is momentarily too low to keep D_3 on. The R_4

current now flows into the base of Q_3, turning it on momentarily and discharging C_2. The dc supply is constant. Therefore C_2 immediately begins to recharge. This provides precise full-wave control.

SOLID-STATE SWITCHING

A solid-state switch can replace the centrifugal starting switch in split-phase and capacitor-start motors. The start winding is usually switched off when the motor attains 75 percent of the base speed. In some applications, the arcing accompanying mechanical switching is undesirable. Solid-state switching is then suitable.

Figure 10-79 shows a solid-state–switched, capacitor-start motor. Current through the start winding (S.W.) is controlled by the solid-state switch. During startup, the current through the run winding (R.W.) is high. This current sensed by the current transformer keeps the solid-state switch on. As the motor speeds up, the transformer current decreases. At some predetermined point, the solid-state switch turns off, and only the run winding remains energized.

THREE-PHASE DRIVES

Three-phase motors are usually large, integral-horsepower motors. Three-phase speed-control drives are available. There are several types of drives: magnetic drives, motor-generator sets, and static drives. Magnetic and motor-generator drives are mechanical-electrical drives. The static drive is purely electronic.

Magnetic Drives

Figure 10-80 shows the mechanical structure of a magnetic drive. The field assembly (stationary field) is bolted to the machine housing and remains stationary. The input assembly is a metal drum mounted on the motor shaft. It is concentric with the field winding and affected by its magnetic field. The output assembly is mounted on the output shaft, and its speed is determined by the control circuitry.

The drive operates as follows: With zero field current, the input assembly is unaffected by the stationary assembly field and rotates freely at motor speed. It has no affect on the output assembly, which remains stationary. When the stationary field is excited and the motor is turning, eddy currents are induced in the input assembly by the stationary field. These eddy currents establish a magnetic field around the input assembly. This magnetic field rotates at motor speed and exerts a torque on the output assembly. The speed of the output assembly depends on its load and the strength of the induced magnetic field in the input assembly. The strength of the field in the input assembly is controlled by the SCR's firing angle in the circuit of Figure 10-81. The firing angle is determined

by a feedback, reference-controlled trigger circuit, similar to those already studied. The feedback signal is usually obtained from a tachometer.

Motor-Generator Drives

Figure 10-82 shows a simplified motor-generator drive. The motor-generator set is part of the control unit, and the dc motors is the controlled motor. The dc voltage output of the generator depends on the speed of the three-phase motor driving it and on its own field excitation. The speed of the dc motor depends on this dc voltage impressed across its armature. The excitation of the generator field depends on the SCR's firing angle. The SCR is controlled by a usually sophisticated feedback-reference trigger circuit.

Static Drives

The static drive shown in Figure 10-83 rectifies three-phase power and drives a dc motor. The motor speed depends on the SCRs' firing angle. Each SCR fires at angles displaced by 120° from one another. Rectified three-phase ac produces a satisfactory dc without filtering, and so the current through the motor armature is rectified but unfiltered. The triggering circuits used here are complicated but use the principles already discussed.

CHOPPER DRIVES

Speed control is often required for dc motors operating from a dc source, for example, golf carts, fork-lift trucks, and other battery-operated electric vehicles. The chopper controller or voltage chopper is widely used in these applications.

The chopper controller chops the dc-source voltage into constant amplitude pulses. Power delivered to the motor is controlled in one of two modes: constant frequency–variable pulse width or variable frequency–constant pulse width.

In the constant frequency–variable pulse-width mode, the chopper operates at a constant frequency. The motor speed is controlled by varying the width (duration) of the pulses. In SCR-controlled circuits, the pulse width is determined by controlling the firing times. Power-transistor drives are also used in chopper-controlled drives. The motor power is then determined by controlling the transistors' turnoff time.

In the variable frequency–constant pulse-width mode, the pulse duration is constant. The motor speed is controlled by adjusting the pulses' repetition rate. SCR and power-transistor circuits are widely used in this application.

Figure 10-84 shows a Jones chopper circuit. This is a popular circuit widely used in fork-lift truck drives. The circuit operates by supplying load current when S_1 is gated on and by blocking load current when S_2 goes on. When S_1 is gated on, the load current flows through S_1, L_2, and the load. At the same time, C is

charged by transformer action through D_1 with its lower plate positive. When S_2 is gated on, the capacitor voltage appears across S_1. S_1 is reversed biased and turns off. The pulse duration and repetition rate are determined by the firing signals at the SCR's gate.

INVERTERS

Inverters convert dc to variable-frequency ac. The speed of inductance and reluctance motors depends most strongly on the frequency of the supply. Therefore inverters are suitable for the speed control of these motors. This same technique can be used to control the speed of ac motors driven by an ac supply. The ac supply is rectified. The output of the rectifier drives an inverter that supplies the ac motor.

Figure 10-85 shows a series inverter. Series inverters are primarily used for fixed-frequency applications, but they are also used as variable-speed controllers. This controller has been successfully used in blower and pump systems.

The frequency of the circuit of Figure 10-85a is controlled by alternate firings of S_1 and S_2. When S_1 is gated on, current flows through C and the load. This provides the positive half-cycle. L, C, and R act to make the current sinusoidal. During this period, C is charged to peak values. When S_2 is gated on, the anode voltage of S_1 drops to ground, and S_1 turns off. C discharges through S_2 and provides the negative half-cycle. S_3 is turned on between cycles to return excess charge to the dc supply.

Three-phase inverters are used to drive and control ac motors. The circuit (Figure 10-86), although more complex, operates like the series inverter of Figure 10-85. The three-phase bridge rectifier supplies dc to the inverter. S_1 and S_4 are fired alternately to invert the load current for one phase. S_2 and S_5, and S_3 and S_6 are fired for the other phases. The diodes in antiparallel with the SCRs provide a path for the reactive current when the SCR turns off. Rigid control of SCR firing is required. An incorrect firing sequence, caused perhaps by noise, can turn on two opposed SCRs at the same time, thereby causing a short across the dc supply.

CYCLOCONVERTERS*

Cycloconverters convert the ac supply voltage to a lower, variable frequency. The cycloconverter is an alternative to a rectifier-inverter system for changing the supply frequency.

Figure 10-87 shows a single-phase cycloconverter. It is a full-wave rectifier with antiparallel SCRs replacing the usual diodes. The SCRs are fired in pairs:

*Adapted from General Electric Co., Semiconductor Products Dept.

SCR_1 and SCR_2 or SCR_3 and SCR_4. SCR_1 and SCR_2 provide the positive half-cycle of the output, and SCR_3 and SCR_4 provide the negative half-cycle. The output frequency is always less than the supply frequency. This frequency is determined by the length of time that the alternate SCR pairs are fired. The amplitude and shape of the output waveform depend on the pattern of firing. Figure 10-88 shows the firing pattern required to generate a sine wave of about one-third line frequency. The sine wave of Figure 10-88 has been filtered to remove the line frequency components. Cycloconverters are widely used to control three-phase induction motors.

MICROPROCESSOR-CONTROLLED MOTOR DRIVES

The advent of the microprocessor and computer has significantly extended the scope of motor control. Motors can be precisely controlled not only in speed but also in acceleration, deceleration, and end position. Motors can also be controlled by programs consisting of many separate commands and made to respond to external conditions.

Microprocessors- and computer-controlled motors are used in automated machine tools and in robots. In both applications they are used to position an element of the machine and then to control some process. This process can be welding, turning, milling, lifting, tightening, and the like. In both cases, precise control of motor speed, position, acceleration, and deceleration are needed. Stepper and servo motors are both used in these applications.

THE STEPPER MOTOR

The stepper motor is a brushless dc motor with an armature that can be positioned by energizing pairs of field coils. Figure 10-89 shows a stepper motor with four stator windings and a permanent-magnet armature. The armature will rotate so that its magnetic field lines up with the energized pair of stator coils. In Figure 10-89b, Step 1 shows the case for *A* and *C* energized. Deenergizing *A* and *C* and energizing *B* and *D* will rotate the armature 90° counterclockwise (Step 2). Energizing *C* and *A* in reverse polarity rotates the armature another 90° counterclockwise. By successively energizing and deenergizing the stator pairs, the armature may be made to rotate in steps through any number of complete revolutions. With proper commutation of the stator fields, the armature can be made to rotate smoothly and continuously at speeds controlled precisely by the switching rate.

The stepper motor is usually driven by pulsing all the stator coils in a desired sequence. Figure 10-89c shows the timing of pulses required to rotate the stator counterclockwise in 90° steps. Positive pulses represent current leaving the stator coil; negative pulses, current entering the stator coil. A pair of coils are energized

when one is made positive and the other, negative. During Step 1, *A* and *C* are energized; during Step 2, *B* and *C*; and so on.

The rotor in Figure 10-89a can be rotated in 45° steps by overlapping pulses. This is shown in Figure 10-89d. During Step 1, *A* and *C* are energized, and the rotor rotates into the 0° position shown before. During Step 2, *A* and *C*, and *B* and *D* are energized. The armature now rotates 45° counterclockwise.

Figure 10-90 shows a variable-reluctance stepper motor with a multipole armature and three pairs of stator coils. In Step 1, *A* and *D* are energized, and the armature aligns its two opposite poles with the stator pair. Energizing *A* and *D* and *F* and *C* rotates the armature 30° clockwise.

The stepper motor can be used as a high-precision positioning device. It is available for angular displacements from 0.9 to 180°. It can also function as a precise speed and acceleration-deceleration device, as it will exactly follow a pulse-train pattern. Because of its inherent precision, feedback is not required.

Stepper-Motor Controllers

Intelligent microprocessor- or computer-controlled stepper-motor controllers are now available. These control step rate, acceleration and deceleration, number of steps, and step direction. In addition, an internal memory can be used to store commands and repeat complex motions. Secondary control lines allow these motions to be synchronized with external events. Using these secondary control lines, an external computer can control several motors and integrate their operation while an intelligent controller runs each motor.

The CY512 intelligent positioning stepper-motor controller manufactured by Cybernetic Micro Systems is a good example. It is supplied in a standard five-volt, 40-pin package and will control any four-phase stepper motor in either full- or half-step modes. It will interface with any computer using parallel input and provides numerous inputs and outputs for auxiliary control. Sequences of commands written in an English-like, high-level language may be programmed into its memory from a standard (ASCII) keyboard. It can output 8,000 steps per second in either direction. Figure 10-91 shows the CY12 pin-out diagram.

A Welding-Machine Application*

A welding machine must make six equally spaced welds on a metal piece. The system must position the welder for each weld and turn it on when correctly positioned. After six welds, it must rapidly reposition itself for the next piece. The preliminary steps required to enter the program and the program itself are as follows:

*Courtesy of Cybernetic Micro Systems.

Preliminaries	
Command	*Meaning*
R 180	Define step rate.
S 35	Set acceleration and deceleration rate.
F 9	Further define step rate.
A	Declare current position as home.
E	Enter and save the following program.
	Program
N 20	Take 20 steps between welds.
+	—in clockwise direction.
W	Wait until workpiece is ready.
G	Go 20 steps.
C	Activate welder.
X1000	Delay 1,000 ms to weld.
B	Turn off welder.
L 6, 5	Repeat 6 times from G command.
P O	Return to home position after 6 welds.
T	Repeat program until no more pieces.
O	Stop program, return to command mode.
	Termination Commands
Q	Exit program mode.
D	Begin executing program.

SERVO SYSTEMS

Servo systems are electromechanical systems that rely on feedback for precise motor control. Figure 10-92 shows a basic closed-loop servo system designed to position a motor precisely. The system consists of an input reference, a servo amplifier, a motor, an integrator, and a feedback network. A tachometer connected to the motor generates a voltage proportional to the velocity. This signal is integrated in the integrator (1/S box) to give the motor's position relative to a starting point (home). The feedback box returns this signal to the input summing point (circle with *X*). The reference and feedback voltage are compared at the summing point. If there is no position error, the output of the summing box is zero, and no power is delivered to the motor. If there is an error, the summing box outputs a positive or negative voltage. The output's polarity depends on the direction of the position error. This output is amplified by the servo amplifier, which delivers power to the motor until it is correctly positioned.

This simple system has some problems, however. Motor and load inertia make it impossible to stop the motor abruptly, and so the motor may overshoot the desired position. Attempts to reposition it correctly can result in hunting or excessive overshoot. Usually, an analog compensation network (Figure 10-93) is installed between the summing point and the amplifier. This network transforms

the signal so that the motor is appropriately slowed down before stopping. This fixed compensation, however, cannot take into account any variations in loading conditions and can at best be only a compromise.

Figure 10-94 shows the modern solution to this problem. The passive analog compensation network is replaced by a microcontroller and a digital-to-analog converter (D/A). The controller is provided with a complete description of the state of the system (present and previous position error and the present and previous amplifier output). It computes the optimal control equation and outputs this as a digital signal to the D/A, which then transforms this into an appropriate control voltage. The computations are carried out in real time so that the motor is controlled almost continuously until it is brought to a smooth stop in the shortest time.

The FPC-1800 Precision Digital Controller* is shown schematically in Figure 10-95. Information from the motor shaft provides present data while previous data is retained by the controller. The controller contains a decoder, a microcomputer, a reference, and a DAC (D/A). Provision is made for external control by a host computer. The FPC-1800 can be interfaced with a host computer and programmed with an English-like, high-level language. It can then be operated under the control of the host.

Programming affords control over the motor's velocity and position. Position instructions can be relative either to the previous position or to an established HOME position. The system can be moved directly to any position relative to HOME. Positioning steps can be programmed for any desired increment. The servo system can be unlocked to allow external repositioning. Relative position commands permit the system to move at a controlled velocity until an internal or external stop instruction is received.

The FPC-1800 has a learn mode. When the system is unlocked and externally moved through a sequence of positions, the position at each step is monitored and learned. These steps can then be repeated under system control. This capability is especially important for instructing robots.

Servo Motors

All types of motors are used as servo motors. Initially, dc motors driven by the controlled dc output of the servo amplifier were used. Now, however, because of widespread interest in servo systems, many new motors, both ac and dc, are being designed specifically for servo systems. These new developments have provided higher torque-weight ratios, greater efficiencies, and more precise control.

The Analine linear dc motor† is an example of the new servo motors. The motor has two elements: a fixed-coil assembly and a movable permanent-magnet

*Finnel Systems.

†Anorad Corp., Hauppage, N.Y.

assembly attached to the positioning assembly. Contact between the two elements is limited to a set of brushes. The positioning assembly is available in lengths from one-half inch to five feet. Assemblies can be joined to give greater lengths. Accelerations up to four g's and speeds from 0.0001 to 60 inches per seconds are available. The attractive force is 120 pounds. The manufacturers claim the motor to be smoother and more precise than a rotating motor driving a ball screw because there are no gears in the system.

A disc armature* is the key to a high torque-to-inertia ratio design. Nineteen ounce-inch to 17 pound-feet with 1/17 to ten horsepowers are available. The disc armature has a much larger diameter than does a comparable iron-core motor, and so it provides significantly more torque. The ironless disc armature is also much lighter and has less inertia than does the traditional iron-core motor. Therefore it can be operated at higher speeds and accelerations.

Several manufacturers market servo systems using ac servomotors. Toshiba International Corporation supplies two such systems for automated machine tools and robots. Rated speeds are 1,500, 3,000, and 4,500 rpm. Torques range from 0.32 to 64 kg-cm. for one type and from 25 to 241 kg-cm. for another. General Electric offers a closed-loop control system using an ac induction motor. Allen-Bradley sells a programmable position controller that uses a standard squirrel-cage induction motor; ac motors eliminate the brush-caused problems found in dc motors.

Servo Motor Drives

Servo amplifiers control motor speed in several ways: dc motors are controlled by varying the dc supply power. Motor speed may be controlled by a power amplifier supplying dc power. In this case the servo amplifier need only be a power amplifier capable of abruptly changing its output voltage. Pulse-width modulation (PWM) is another popular technique. Here a dc power source is chopped into pulses at high frequencies. The widths of these pulses are modulated by the error signal. This output supplies the motor directly. In addition, ac motors can also be controlled by PWM. Phase control is also used to control dc and ac motors.

Dynamic stiffness is an important measure of servo performance. This is defined as the ratio of an abrupt change in thrust to the resulting change in load position. Good performance requires a high and constant dynamic stiffness. A typical dynamic stiffness for a three-phase, phase-controlled system is 13.8×10^6 lb/in. For a PWM servo system, it is 49×10^6 lb/in.

The future of microprocessor- and computer-controlled servo mechanisms is promising. Individual controls will become more intelligent and adaptive. They

*Kolmorgen's PMI Motors, Syosset, N.Y.

will be sophisticated enough to sense the system's response and adjust automatically for optimal damping. For robotics this means that the central computer can be relieved of this task and concentrate on target positions, as humans do. Servo systems that communicate over a network already exist and will lead to automated factories directed by a central library. But because of the longevity and cost of machine tools, these new developments will evolve slowly. Ultimately, however, motors and motor controls will reach new levels of sophistication.

APPENDIX

TABLE 1 Table for Bare Copper Wire

AWG	*Diameter, Inches*	*Circular Mils*	*Pounds per 1000 ft*	*Ohms at 68°F. per 1000 ft*
0000	0.4600	211,600.0	640.5	0.0490
000	0.4096	167,800.0	507.9	0.0618
00	0.3648	133,100.0	402.8	0.0779
0	0.3249	105,500.0	319.5	0.0982
1	0.2893	83,694.0	253.3	0.124
2	0.2576	66,370.0	200.9	0.156
3	0.2294	52,630.0	159.3	0.197
4	0.2043	41,740.0	126.4	0.248
5	0.1819	33,100.0	100.2	0.313
6	0.1620	26,250.0	79.46	0.395
7	0.1443	20,820.0	63.02	0.498
8	0.1285	16,510.0	49.98	0.628
9	0.1144	13,090.0	39.63	0.792
10	0.1019	10,380.0	31.43	0.998
11	0.09074	8,230.0	24.92	1.260
12	0.08081	6,530.0	19.77	1.588
13	0.07196	5,170.0	15.68	2.003
14	0.06408	4,107.0	12.43	2.525
15	0.05707	3,257.0	9.858	3.184
16	0.05082	2,583.0	7.818	4.016
17	0.04526	2,048.0	6.200	5.064
18	0.04030	1,624.0	4.917	6.385
19	0.03589	1,288.0	3.899	8.051
20	0.03196	1,022.0	3.092	10.15
21	0.02846	810.1	2.452	12.80
22	0.02535	642.4	1.945	16.14
23	0.02257	509.5	1.542	20.36
24	0.02010	404.0	1.223	25.67
25	0.01790	320.4	0.9699	32.37
26	0.01594	245.1	0.7692	40.81
27	0.01420	201.5	0.6100	51.47
28	0.01264	159.8	0.4837	64.90
29	0.01126	126.7	0.3836	81.83
30	0.01003	100.5	0.3042	103.2
31	0.00892	79.70	0.2413	130.1
32	0.00795	63.21	0.1913	164.1
33	0.00708	50.13	0.1517	206.9
34	0.00630	39.75	0.1203	260.9
35	0.00561	31.52	0.09542	329.0
36	0.00500	25.00	0.07568	414.8
37	0.00445	19.83	0.0601	523.1
38	0.00396	15.72	0.04759	659.6
39	0.00353	12.47	0.03774	831.8
40	0.00314	9.888	0.02990	1,049.0

ADDITIONAL INFORMATION ON COPPER WIRE

This wire table can be remembered very easily if a few simple points are kept in mind:

1. A wire three sizes smaller than another wire has half the area of the larger wire. For instance, No. 20 AWG copper wire has half the area of No. 17 AWG. Therefore, two No. 20 wires in parallel have the equivalent area of one No. 17.
2. A wire three sizes smaller than another wire has twice the resistance of the larger wire.
3. A wire three sizes smaller than another wire has half the weight of the larger wire.
4. A No. 10 AWG copper wire is approximately 0.10 inch in diameter, has an area of approximately 10,000 circular mils and has a resistance of 1 ohm per 1000 feet.

Although it is much better to use the same size wire in rewinding a motor as was used in the original winding, sometimes circumstances make it necessary to substitute another size. Table II shows equivalent wire sizes:

TABLE II Wire-size Equivalents

Wires Not Available	*Use*	*Wires Not Available*	*Use*
No. 10	Two No. 13	Two No. 28	One No. 25
No. 11	Two No. 14	Two No. 27	One No. 24
No. 12	Two No. 15	Two No. 26	One No. 23
No. 13	Two No. 16	Two No. 25	One No. 22
No. 14	Two No. 17	Two No. 24	One No. 21
No. 15	Two No. 18	Two No. 23	One No. 20
No. 16	Two No. 19	Two No. 22	One No. 19
No. 17	Two No. 20	Two No. 21	One No. 18
No. 18	Two No. 21	Two No. 20	One No. 17
No. 19	Two No. 22	Two No. 19	One No. 16
No. 20	Two No. 23	Two No. 18	One No. 15

TABLE III Motor Full Load Currents

	Direct Current (Running at Base Speed)			
HP	*90V*	*180V*	*240V*	*500V*
¼	4.0	2.0	1.6	
⅓	5.2	2.6	2.0	
½	6.8	3.4	2.7	
¾	9.6	4.8	3.8	
1	12.2	6.1	4.7	

continued

continued

	Direct Current (Running at Base Speed)			
HP	*90V*	*180V*	*240V*	*500V*
1½		8.3	6.6	
2		10.8	8.5	
3		16.0	12.2	
5		27.0	20.0	
7½			29	13.6
10			38	18
15			55	27
20			72	34
25			89	43
30			106	51
40			140	67
50			173	83
60			206	99
75			255	123
100			341	164
125			425	205
150			506	246
200			675	330
Over 200 HP Approx. Amps/HP			3.4	1.65

TABLE IV Motor Full Load Currents

	Single Phase	
HP	*115V*	*230V*
⅙	4.4	2.2
¼	5.8	2.9
⅓	7.2	3.6
½	9.8	4.9
¾	13.8	6.9
1	16	8
1½	20	10
2	24	12
3	34	17

continued

continued

HP	*Single Phase* *115V*	*230V*
5	56	28
7½	80	40
10	100	50

TABLE V Maximum Locked Rotor Currents

	3—Phase Motors					
	Voltage					
HP	*200*	*220/230*	*440/460*	*550/575*	*2300*	*4160*
½	23	20	10	8		
¾	29	25	12.5	10		
1	34.5	30	15	12		
1½	46	40	20	16		
2	57.5	50	25	20		
3	73.5	64	32	25		
5	106	92	46	37		
7½	146	127	63	51		
10	186	162	81	65		
15	267	232	116	93		
20	334	290	145	116		
25	420	365	182	146	35	19
30	500	435	217	174	41	23
40	667	580	290	232	55	30
50	834	725	362	290	69	38
60	1000	870	435	348	83	46
75	1250	1085	592	435	104	57
100	1670	1450	725	580	139	76
125	2085	1815	907	726	173	96
150	2500	2170	1085	870	208	115
200	3340	2900	1450	1160	278	153
250	4200	3650	1825	1460	349	193
300	5050	4400	2200	1760	420	232
350	5860	5100	2550	2040	488	270
400	6670	5800	2900	2320	555	306
450	7470	6500	3250	2600	620	344
500	8340	7250	3625	2900	693	383

Based on NEMA Standards MGI—12.34 January 1984

TABLE VI Motor Full Load Currents

3 Phase A.C. Induction Type—Squirrel Cage and Wound Rotor

HP	*115V*	*200V*	*230V*	*460V*	*575V*	*2300V*	*4160V*
½	4	2.3	2	1	.8		
¾	5.6	3.2	2.8	1.4	1.1		
1	7.2	4.15	3.6	1.8	1.4		
1½	10.4	6	5.2	2.6	2.1		
2	13.6	7.8	6.8	3.4	2.7		
3		11	9.6	4.8	3.9		
5		17.5	15.2	7.6	6.1		
7½		25	22	11	9		
10		32	28	14	11		
15		48	42	21	17		
20		62	54	27	22		
25		78	68	34	27		
30		92	80	40	32		
40		120	104	52	41		
50		150	130	65	52		
60		177	154	77	62	16	8.9
75		221	192	96	77	20	11
100		285	248	124	99	26	14.4
125		358	312	156	125	31	17
150		415	360	180	144	37	20.5
200		550	480	240	192	49	27

Over 200 HP
Approx.
Amperes/HP 2.75 2.40 1.20 .96 .24 .133

TABLE VII Possible Synchronous Speeds

Poles	*60 Cycles*	*50 Cycles*	*40 Cycles*	*25 Cycles*
2	3600	3000	2400	1500
4	1800	1500	1200	750
6	1200	1000	800	500
8	900	750	600	375
10	720	600	480	300
12	600	500	400	250
14	514.2	428.6	343	214.3
16	450	375	300	187.5
18	400	333.3	266.6	166.6
20	360	300	240	150
22	327.2	272.7	218.1	136.3
24	300	250	200	125

continued

continued

Poles	*60 Cycles*	*50 Cycles*	*40 Cycles*	*25 Cycles*
26	277	230.8	184.5	115.4
28	257.1	214.2	171.5	107.1
30	240	200	160	100
32	225	187.5	150	93.7
34	212	176.5	141.1	88.2
36	200	166.6	133.3	83.3
38	189.5	157.9	126.3	78.9
40	180	150	120	75
42	171.5	142.8	114.2	71.4
44	163.5	136.3	109	
46	156.6	130.5	104.3	
48	150	125	100	
50	144	120	96	
52	138.5	115.4	92.3	
54	133.3	111.1	88.9	

TABLE VIII Chord Factor for Slots per Pole

Span	*Slots/Pole*							
	6	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1–3	.50	.43	.38	.34					
1–4	.71	.62	.55	.50					
1–5	.87	.78	.71	.64	.59				
1–6	.97	.90	.83	.77	.71	.65	.61		
1–7	1.00	.97	.92	.87	.81	.76	.71	.66	.62
1–8	.97	1.00	.98	.94	.89	.84	.79	.75	.71
1–9		.97	1.00	.98	.95	.91	.87	.82	.78
1–10			.98	1.00	.99	.96	.92	.89	.85
1–11				.98	1.00	.99	.97	.94	.90
1–12					.99	1.00	.99	.97	.94
1–13						.99	1.00	.99	.97
1–14							.99	1.00	.99
1–15								.99	1.00
1–16									.99

TABLE IX NEMA Code Letters

NEMA Code Letter	*Locked Rotor KVA Per HP*	*NEMA Code Letter*	*Locked Rotor KVA per HP*
A	0–3.15	L	9.0–10.0
B	3.15–3.55	M	10.0–11.2
C	3.55–4.0	N	11.2–12.5
D	4.0–4.5	P	12.5–14.0
E	4.5–5.0	R	14.0–16.0
F	5.0–5.6	S	16.0–18.0
G	5.6–6.3	T	18.0–20.0
H	6.3–7.1	U	20.0–22.4
J	7.1–8.0	V	22.4 and up
K	8.0–9.0		

NEMA Standards MG 1-10.36, January 1984

Code Letters Usually Applied to Ratings of Motors Normally Started on Full Voltage

Code Letters		F	G	H	J	K	L
Horse-power	3-phase	15 up	10–7½	5	3	2–1½	1
	1-phase	–	5	3	2–1½	1¾	½

NEMA Standards MG 1-10.36, January, 1984

CHAPTER 1 STUDY QUESTIONS

1. Give a description of a capacitor motor.
2. What is the difference between a capacitor-start motor and a permanent-split capacitor motor?
3. Name the main parts of a capacitor-start motor.
4. (a) Draw a schematic diagram of a capacitor-start motor. (b) Draw a schematic diagram of a permanent-split capacitor motor.
5. Draw a schematic of a two-value capacitor motor.
6. Name the parts of a squirrel-cage rotor.
7. What are the symptoms of an open rotor?
8. When a capacitor-start motor starts, (a) How many windings are energized? (b) What happens after the motor reaches 75 percent of its loaded speed?
9. Explain the action of the centrifugal switch system.
10. Explain what happens when a capacitor-start motor is energized.
11. Name the parts of an electrolytic capacitor.
12. What two components determine the capacitor's rating?
13. (a) What happens when the foil area is increased? (b) when the dielectric thickness is increased?
14. What happens to the current when the microfarad rating is increased?
15. What is the purpose of the paper in an electrolytic capacitor?

16. What is the purpose of the aluminum oxide?
17. What is the purpose of the electrolyte?
18. What is the main difference between an electrolytic capacitor and an oil-filled capacitor?
19. Explain the sine wave.
20. Explain the difference between electrical degrees and mechanical degrees.
21. What two measurements does the horizontal line of the sine wave represent?
22. Explain the difference between cycle and Hertz (Hz).
23. How is one cycle generated?
24. Draw a sine wave that includes the current in an inductive circuit.
25. Name three conditions that create inductive reactance in a circuit.
26. What effect does inductive reactance have on the current?
27. What effect does capacitive reactance have on the current?
28. What creates the rotating magnetic field in a two-phase stator? (a) the voltage (b) the current (c) the 90° separation of the current flow of the two windings
29. How much time does 90° represent in a sixty-cycle per second (Hz) circuit?
30. What happens within the windings of a rotor when the stator is energized?
31. Why is it important to place the start and run winding 90 electrical degrees apart in the stator?
32. In motors of the same size, what is the difference between the run winding of a capacitor motor and a split-phase run winding?
33. What is the difference between the start winding of a split-phase and the start winding of a capacitor-start motor?
34. Give two reasons why a split-phase motor does not have the starting power that the capacitor-start motor has.
35. Describe what happens when a split-phase motor is energized.
36. What are the steps used for analyzing the repairs a motor needs?
37. What is the most common problem that develops in a capacitor-start or a split-phase motor?
38. Describe "dead spot" and its cause.
39. When installing thrust washers, what two components must be kept in alignment?
40. What will cause a terminal bolt to become charred?
41. Where is the most common place for an open to occur in a winding?
42. What is the first thing that is done to the end plate and the stator before disassembling the motor?
43. Name the information that should be documented before a motor is stripped.
44. What will the number of poles determine in a motor?
45. Name the data that is destroyed when the wires are stripped from the stator.
46. Why is it important to record the end room for the coil groups?
47. If 30 turns are counted in a coil that is wound two in hand or two in parallel, how many actual turns are in the coil?
48. What terminal numbers are used for a dual-voltage run winding?
49. What are the terminal numbers used for a dual-voltage start winding?
50. What numbers are used for (a) a single-voltage run winding and (b) a single-voltage start winding?

51. Define standard rotation.

52. What terminal numbers are combined to obtain standard rotation?

53. Draw (a) a pole group as it would appear before it is placed in the stator and (b) a pole group as it appears on a straight-line diagram including the arrow that indicates current flowing in the left side and exiting the right side of the group.

54. Draw a one-circuit, four-pole, run-winding diagram, indicating with arrows the direction of current flow through each group. Assume the current is going in T1 and out T4.

55. Draw a two-circuit, four-pole run winding and show the direction of current flow.

56. How many circuits are possible in a four-pole run winding that is wound with single-circuit coil groups?

57. Name all the circuits possible for an eight-pole run winding with single-circuit pole groups.

58. Why are multiples of small wires used instead of one large wire?

59. In a dual-voltage one- and two-circuit run winding, how many circuits would there be if the motor is connected (a) high voltage? (b) low voltage?

60. In a dual voltage two- and four-circuit motor, how many circuits would there be if the motor were connected (a) high voltage? (b) low voltage?

61. What numbers go together for the low-voltage connection?

62. What numbers go together for high voltage?

63. What is a two-circuit coil group?

64. Name all the circuits possible in a six-pole run winding that has two-circuit coil groups.

65. How many circuits do most start windings have?

66. What is the difference between long jumper and short jumper?

67. Give all the terms that mean short jumper.

68. Give all the terms that mean long jumper.

69. What happens to the insulation when a motor is operated at a temperature higher than the insulation's class?

70. What is the temperature classification based on?

71. Why must slot liners fit as exactly as possible?

72. What must be checked before slot liners are inserted?

73. What determines the class of insulation that is selected for a motor?

74. What is the accepted voltage limit between magnet wires without using additional insulation?

75. Why should the connection sequence be started at 6 o'clock position and proceed counterclockwise around the stator?

76. What is the rule for connecting adjacent poles in a winding?

77. Draw a four-pole, one-circuit (series-connected) run winding using the straight-line method with rectangular blocks. Connect it short jumper.

78. Draw a four-pole, one-circuit start winding with one capacitor and one switch. Connect it short jumper.

79. Draw a straight-line diagram of a complete four-pole capacitor-start motor. Connect both the start- and run-winding one circuit, short jumper. Use the proper numbers for both windings.

80. Draw a circular diagram of the motor in question 79.

81. What numbers are together for clockwise rotation facing the shaft?

82. What numbers are together for counterclockwise rotation facing the shaft?
83. Name the five steps used when making connections.
84. What are the requirements for a good connection?
85. What welding methods are used to make connections?
86. Why must aluminum wire be sealed from air exposure?
87. What should be checked before a stator is varnished?
88. What are the reasons for varnishing a winding?
89. Describe the function of a thermal-overload device.
90. (a) When is terminal P2 not used? (b) Does the current through P2 affect the function of the device?
91. Which terminal is always connected to the line by itself?
92. The current through which terminal will cause the device to open?
93. What can happen if T3 is shorted?
94. If the motor is dual voltage, which ampere rating is the element of the protective device designed for? (High or low voltage?)
95. Draw a schematic diagram of a single voltage motor with a thermal protector.
96. Draw a schematic diagram of a dual-voltage motor with a thermal protector and connect it for low voltage.
97. Draw a schematic of the motor in question 96 connected for high voltage.
98. How is a capacitor-start motor reversed?
99. Would an eight-pole have higher speed than a two-pole motor?
100. Draw a straight-line diagram of a four-pole, short-jumper, single-circuit start and single-circuit run capacitor-start motor.
101. Draw a straight-line diagram of the same motor as in question 100 with a two-circuit run winding.
102. Does single voltage mean high voltage or low voltage?
103. Draw a diagram of a single-voltage, four-pole, short-jumper, nonreversable capacitor-start motor.
104. Draw the same motor as in question 103 but connect the start winding so that it will receive one half of applied voltage.
105. Would the motor in question 104 be used on high or low voltage?
106. Draw a single-voltage four-pole motor with an overload device, connected short jumper.
107. Why is P2 not used in a single-voltage motor?
108. List the colors that go with T1, T2, T3, T4, T5, and T8.
109. Draw a straight-line diagram of a dual-voltage, four-pole, short-jumper, capacitor-start motor with a thermal overload and connect it for low voltage.
110. Draw the same motor as above and connect it for high voltage.
111. Draw a straight-line diagram of a dual-voltage, four-pole, short-jumper, capacitor-start motor with a dual-voltage start winding that has one set of start-switch contacts.
112. Draw the same motor as in question 111 with two sets of start-switch contacts.
113. What is the voltage rating of the capacitors used with a dual-voltage start winding?
114. Describe the layered run winding.
115. What is the advantage of winding both sections together?

116. How many circuits are possible in a four-pole layered winding?
117. Why is P2 used when a dual-voltage motor is connected low voltage?
118. What is the function of a current relay when used in a capacitor-start motor?
119. What is the "at rest" position of the current relay contacts?
120. Describe what happens when a motor using a current relay is energized.
121. What happens if the motor is too large for the current relay? Too small?
122. Draw a schematic of a capacitor-start motor with a current relay.
123. Why is the current relay connected in series with one section of the run winding in a dual-voltage motor?
124. What determines the wire size for the coil of a current relay?
125. What is the at rest position of the contacts in a potential relay?
126. How is the coil of the potential relay connected in relation to the start winding?
127. What makes the coil function at 75 percent of full speed?
128. Why does the coil continue to function after the start contacts are open?
129. What percent of the line voltage will make the coil open the contacts?
130. Draw a schematic of a motor using a potential relay.
131. What will happen if the capacitor is in the relay coil and start-winding circuit?
132. What factors must be considered when replacing a centrifugal device and stationary switch with a potential relay?
133. What voltage rating should a potential relay have when used on a dual-voltage motor?
134. How can the voltage rating of an unmarked voltage relay be determined?
135. Draw a straight-line diagram of a four-pole, short-jumper, capacitor-start motor with three leads and number the leads (single-circuit, start, and run).
136. When a motor has a centrifugal device, why is it necessary to stop it before it can be reversed?
137. Name two devices that will allow instant reversal of a capacitor-start motor.
138. Draw a schematic of a two-speed motor with two run windings and one start winding. Include an external selector switch.
139. Which run winding is always connected to the normally open contacts?
140. Why is it necessary to use a centrifugal device that functions at a speed lower than 75 percent of the high speed?
141. When all the poles of a consequent pole two-speed, capacitor-start motor have the same polarity, will the speed be high or low?
142. Which of the following speeds found on a name plate would indicate a consequent-pole motor? (a) 1750/1140 (b) 1800/900 (c) 1750/1460.
143. Why are permanent split-capacitor run motors good for fan duty?
144. Draw a schematic of a four-pole, single-voltage, permanent split-capacitor run motor.
145. Why does the capacitor determine which winding becomes the start winding in the motor described as special-duty, reversable-capacitor motor?
146. What is the rule for determining rotation when the polarity of the start poles and the run poles is known?

147. Draw a straight-line diagram of a four-pole, short-jumper, dual-voltage, permanent split-capacitor motor.

148. (a) Why does the speed decrease when a lower speed is selected on a loaded two-speed, permanent split-capacitor motor? (b) What happens to the speed when the load is removed?

149. Why would the low-speed winding immediately burn if it is connected to the line voltage?

150. Draw a straight-line diagram of a four-pole, short jumper, three-speed, permanent split-capacitor motor with an external speed selector switch. Connect the start winding in parallel with the high-run winding. Trace the current flow when high speed is selected with a red color. Do the same with medium speed in blue and low speed with green. Why are there less amperes at low speed than at high speed?

151. In a two-value capacitor motor, what effect does the oil-filled capacitor have on the line amperes? The run-winding amperes?

152. Where are oil-filled capacitors *always* connected in two-value capacitor start motors?

153. Oil-filled capacitors are always connected (a) parallel with (b) in series with each other.

154. Draw a straight-line diagram of a one-circuit, four-pole, short-jumper, start winding with two electrolytic capacitors in parallel.

155. Why are two small electrolytic capacitors used in place of one large one?

156. Draw a start winding like the one in question 154 and connect two electrolytic capacitors in series.

157. What voltage is used when two electrolytic capacitors are connected in series?

158. Why must the mfd rating of electrolytic capacitors in series be the same?

159. Draw a straight-line diagram of a four-pole, short-jumper, one- and two-circuit (dual-voltage) start winding with two capacitors and two switch contacts.

160. Explain in detail the steps and calculations necessary in rewinding a capacitor-start motor for a change in voltage.

161. What is the difference between actual turns and effective turns?

162. What condition can cause excessively high voltage across a capacitor?

163. What test result would indicate that a capacitor has no moisture content?

164. How would a capacitor-start motor be effected by (a) a capacitor that is too small for it? (b) a capacitor that is too large for it?

165. What is the recommended operating temperature limit for an electrolytic capacitor?

166. What percent of difference between the voltage across the start winding and the capacitor indicates that the mfd is right for the motor?

167. What two effects will a capacitor that is too small have on a motor?

168. What is wrong with a capacitor that does not spark when using the charge-discharge test?

169. Will an ohmmeter show the mfd value of a capacitor?

170. Describe how an ohmmeter reacts to (a) a shorted capacitor, (b) an open capacitor, (c) a capacitor that is normal.

171. What would be the multiplier for finding a capacitor's value if the test voltage is 130 volts?

172. Name four reasons for premature capacitor failure.

173. (a) What will happen to a loaded motor if, when started, the start contacts open too soon? (b) Name three conditions that could cause this.

174. Draw a schematic of the start winding for a two-value, capacitor-start motor that has one electrolytic capacitor and three oil-filled capacitors.

175. What is the purpose of an oil-filled capacitor?

176. Describe how the oil-filled capacitor is connected in the circuit and how they are connected in relation to each other.

177. What happens when an oil-filled capacitor is shorted? Draw a schematic diagram showing the current flow with this condition.

178. Why should a motor with unknown problems be tested with limited current?

179. Name three reasons why a start winding could test open.

180. (a) Why should the two sections of a dual-voltage run winding have the same ampere reading? (b) What would indicate that one section has a few turns shorted together?

181. What test would show that a motor is grounded?

182. If one circuit in a dual-voltage, reversible capacitor-start motor has a ground, describe how to locate the circuit with the ground.

183. Name two defects that can be found in a thermal device.

184. If the rotor is not aligned with the stator, what effect will this condition have on the amperes?

185. Give five reasons why a motor will not start when it is energized.

186. What is the symptom of an open rotor?

187. How can open rotor bars be located?

CHAPTER 2 STUDY QUESTIONS

1. Name the different types of repulsion motors and give the characteristics and applications of each.

2. (a) What construction features are common to each type of repulsion motor? (b) Describe the different types of commutators used on repulsion motors.

3. (a) Name and describe the main parts of the repulsion-start induction motor. (b) Why is this motor so named?

4. Explain in detail the principle of operation of a repulsion-start induction motor.

5. Describe the construction and operation of two types of centrifugal short-circuiting mechanisms used on repulsion-start induction motors.

6. (a) What is the function of the short-circuiting device on repulsion-start motors? (b) How will the operation of the motor be affected if the device does not function?

7. (a) Name the different parts of the brush-lifting type of centrifugal mechanism and prepare a diagram showing the order in which they are placed on the armature. (b) What function does the governor spring have? (c) How is the pressure of the spring varied?

8. What troubles are likely to occur (a) when the short-circuiting necklace

becomes dirty and does not make good contact with the commutator? (b) when the brushes do not lift off the commutator?

9. (a) Why are brushes necessary for the operation of a repulsion-start induction motor? (b) What would happen if one brush was broken and did not contact the commutator?

10. Describe the construction of the stator core and the stator winding of a repulsion-start induction motor.

11. (a) In making the internal connections how would you make sure that the polarity is correct? (b) Why are four leads brought out of most repulsion motors?

12. In winding the stator, why is it important that each pole be in exactly the same slots as in the original winding?

13. (a) Explain how to take and record data for the stator winding of a repulsion-start motor. (b) Show a sample data chart.

14. (a) What precautions should be taken when replacing commutators on repulsion motors? (b) What information is needed when ordering a new commutator?

15. (a) Explain the difference between a lap and wave winding, and show a simple diagram of each. (b) What advantage has one winding over the other? Explain.

16. After rewinding a stator explain the tests you would give it in order to detect any defects.

17. (a) What data should be taken while stripping an armature of a repulsion-start motor? (b) Show a data chart with sample data. (c) Why is it necessary to record the name-plate data?

18. (a) Describe a step-by-step procedure for winding an armature for a repulsion-start motor. (b) What advantage is there in putting bottom leads into the commutator as each coil is wound, rather than waiting until the entire armature is wound?

19. (a) Diagram and explain the difference between a one-, two- and three-coil-per-slot armature winding. (b) How does the number of commutator bars compare with the number of slots in these different windings?

20. (a) Show a diagram of six coils of a two-coil-per-slot lap-wound armature connected to a commutator. (b) Repeat for a wave-wound armature.

21. (a) What are equalizer connections? (b) What purpose do they serve? (c) What would be the effect on the operation of a motor if the equalizer or cross connections were left out?

22. (a) How are armatures with cross-connections tested for short circuits? (b) Explain why a growler short-circuit test cannot be used. (c) Where are short circuits likely to occur in this armature and what steps would you take to eliminate them in each case?

23. (a) Explain the formula for determining the commutator pitch for a wave-wound armature. (b) Give several examples of how to find pitch. (c) Why don't wave-wound armatures have cross connections?

24. (a) Show by diagram why the rotation of a repulsion-start motor can be reversed by shifting the brushes. (b) How do you determine the amount of shift necessary?

25. Describe the construction of carbon brushes used on repulsion motors.

26. (a) What is meant by the neutral point in a repulsion-start motor? (b) How is this point located? (c) Why is it necessary sometimes to locate the neutral point? (d) What is the soft neutral point and how is it recognized?

27. (a) What would happen if there were an open between brush connections? (b) Will the operation of the motor be affected if the brush holders are grounded in a repulsion-start motor? Why?

28. (a) How does the repulsion motor differ from the repulsion-start induction motor? (b) How can you recognize the difference by inspection?

29. (a) What is a compensating winding and how is it connected in the circuit? Illustrate in a diagram. (b) Why do some repulsion motors have a compensating winding?

30. (a) Show a diagram of a four-pole compensated-repulsion motor; a two-pole motor; a six-pole motor. (b) What factors regulate the speed of these motors?

31. (a) How can the repulsion-induction motor be distinguished from the other types of repulsion motors? (b) Is this possible just by inspection? Why?

32. Explain the operation of an electrically reversible repulsion motor.

33. By means of an example describe how you would rewind a repulsion motor stator for a change in voltage.

34. (a) What are some of the reasons why a repulsion motor will refuse to start when the switch is closed? (b) Explain how current will flow in the motor if the brushes are not connected to the line.

35. How many line wires are used (a) for a repulsion motor? (b) for a single-phase motor?

36. (a) Explain why the wrong brush-holder position may prevent a repulsion-type motor from starting. (b) How do you determine the correct position of the brushes? (c) What will happen if the brushes are not moved sufficiently?

37. (a) What effect will worn bearings have on the operation of a repulsion-type motor? (b) How are worn bearings detected? (c) Explain how they are removed and replaced.

38. (a) How will a dirty commutator affect the operation of a repulsion-start induction-run motor? (b) How will it affect the other types of repulsion motors?

39. (a) Describe the operation of a repulsion-start induction motor that has a defective governor spring. (b) How do you determine the correct spring tension?

40. Of all the single-phase motors that you have studied, which in your opinion has the highest starting torque? the lowest starting torque? Explain your answer.

41. What are some possible troubles if a repulsion-type motor blows a fuse when the switch is put on?

42. (a) List several causes of sparking at the commutator in a repulsion-start induction motor. (b) What procedure would you follow to determine the exact cause of sparking?

43. (a) Draw a diagram of a dual-voltage eight-pole stator of a repulsion-induction motor. Show connections for both voltages. (b) How do you identify the four leads coming out of the motor in order to make the right connection?

44. If you were called upon to repair a repulsion-start induction motor which has stopped running, list the steps you would take in order to put the motor into running condition.

CHAPTER 3 STUDY QUESTIONS

1. Name the parts of a three-phase motor.
2. How is each phase of a three-phase motor similar to the run winding of a capacitor-start motor?

3. Why are the three windings placed in the stator exactly 120 electrical degrees apart?
4. What creates the rotating magnetic field in a three-phase stator?
5. What determines where the center of the magnetic pole is formed in a coil group?
6. Why is there a voltage and current present in the rotor when the stator is energized?
7. How are the poles formed in the rotor?
8. What is synchronous speed?
9. Why is there very little torque produced when the rotor reaches synchronous speed?
10. What is slip?
11. Why is slip necessary?
12. Name the four variations in the construction of the winding in a squirrel-cage rotor that can vary the current that flows in it.
13. Will the amount of current that flows in the rotor winding affect the amount of current that flows in the stator?
14. What does the code letter on the nameplate signify?
15. What is the highest temperature a stator should reach when it is burned for stripping?
16. What can happen if the stator gets too hot?
17. What does the design letter signify?
18. What does the code letter mean?
19. What is meant by rating or duty?
20. Explain service factor.
21. Why should the connection side of a stator be marked?
22. What data will be destroyed when a motor is stripped?
23. What is the difference between the lap and the concentric winding?
24. What are the two types of lap windings?
25. Describe the mush or random-wound coil.
26. What is a group or gang-wound coil group?
27. Why is it necessary to insulate one group from the other?
28. What is the rule used to find the number of coils per phase in a lap-wound stator?
29. How many groups are there in each pole of a three-phase motor?
30. Each group is a pole of one phase. What two terms are used when referring to them?
31. How is the number of groups in a stator determined?
32. How is the number of coils per group determined?
33. Describe how the pole groups of each phase are connected.
34. Why is it recommended to skip the first pole group of the B phase when connecting a three-phase winding?
35. Draw each phase of a four-pole, short-jumper, three-phase motor separately. Draw the A phase in red, the B phase in blue, and the C phase in green.
36. Draw a straight-line diagram of a four-pole, short-jumper, three-phase winding connected one Y. Color each phase as in question 35. Number the groups 1–12 and show the direction of current flow.
37. Draw a circular diagram of the same winding described in question 36. Number the groups and show the direction of current flow.

38. What is the main purpose of a schematic diagram?

39. Give the number of poles and identify this connection: Six-pole groups, one connection containing wires from three pole groups, and three line leads, each fastened to a pole group.

40. How many poles would a motor have if there are (a) 6-pole groups? (b) 12-pole groups? (c) 18-pole groups?

41. Given the following data what is the connection and the number of poles: Twelve-pole groups and two group wires connected to each of three-line leads?

42. What is the connection and number of poles for these data: Eighteen-pole groups, three wires connected to each of three-line leads and three connections, each containing three-group leads?

43. What is the connection and number of poles for these data: Twelve-pole groups, four wires connected to each of three-line leads and four connections containing the ends of three-pole groups?

44. Does the voltage per coil become higher when a dual-voltage motor is connected for high voltage?

45. How many leads are on most dual-voltage three-phase motors?

46. Draw a schematic for a dual-voltage one- and two-wye motor.

47. Draw a schematic showing the spiral method for identifying the lead numbers of a dual-voltage wye and a dual-voltage delta motor.

48. True or false: The high-voltage connection has more groups connected in series than the low-voltage connection in a dual-voltage motor.

49. Draw a straight-line diagram of a four-pole, one- and two-delta, dual-voltage, nine-lead motor connected short jumper.

50. Draw the same diagram as in question 49 and connect it one and two wye.

51. Give the number combinations for both high and low voltage for a dual-voltage wye-connected motor.

52. Give the number combinations for both high- and low-voltage for a dual-voltage delta connected motor.

53. Explain the voltage change with the wye-delta connection.

54. What would happen if a wye-connected motor was connected delta by mistake?

55. What would happen if a delta-connected motor was connected wye by mistake?

56. What is the difference between the diagram in Figure 3-84 and the diagram in Figure 3-89c?

57. Draw a straight-line diagram of a two-pole, one- and two-delta motor.

58. Name five rules for connecting a three-phase winding.

59. Adjacent coil groups in a three-phase motor are (a) coil groups that are next to each other, (b) every other coil group, (c) the next coil group that is of the same phase.

60. Give five names that are used to signify short jumper.

61. Describe long jumper.

62. Is there any advantage in long jumper over short jumper?

63. When is it not possible to use long jumper?

64. Why do motor manufacturers prefer the concentric winding design over the lap method?

65. How is phase B located when connecting a concentric winding?

66. Assuming the motor has no nameplate, there are nine leads coming out of the motor, three of the line leaders are connected four pole groups and two coil groups are connected to each of the remaining six leads, what is the connection?

67. If a two-wye motor has two B-phase ends with one A-phase end connected in one wye and two C-phase ends with one A-phase end connected in the other, would this motor run? Draw a schematic of this connection.

68. How would a repairperson know if a motor is wound using odd-pole grouping?

69. What is the advantage of a 12-lead connection?

70. What lead numbers would identify a motor as part winding start?

71. Are the part-winding start numbers the same as wye-delta?

72. Name three other connections that use six leads.

73. What is the difference between the six-pole groups of a two-pole winding and the six-pole groups of a four-pole consequent pole winding?

74. How many circuits are there in a nine-lead, dual-voltage, wye-connected motor?

75. What is the first test that should be given to an old winding before identifying unmarked leads?

76. How many circuits are in a nine-lead, dual-voltage, delta-connected motor?

77. How does the consequent-pole, two-speed motor get two speeds?

78. Why is the high speed twice that of the low speed?

79. What is the rule for the coil span of consequent-pole motors?

80. Name three consequent-pole connections.

81. (a) Draw the A phase of a one-delta, long-jumper winding showing the polarity. (b) Draw the A phase of a four- and eight-pole constant-torque winding. Show the polarity in one color connected one delta and in another color connected two wye.

82. Explain why the torque remains the same at both high and low speeds.

83. Define one horsepower.

84. When the speed is changed on a constant-torque motor, what happens to the horsepower? Why?

85. Is it possible to make a short-jumper, four- and eight-pole, consequent-pole connection?

86. Draw a straight-line diagram of a constant-torque, four- and eight-pole winding. Use red for the A phase, blue for the B phase, and green for the C phase.

87. Draw the A phase of a constant-horsepower, four- and eight-pole motor. Show the polarity in one color when connected one delta. Show the polarity in another color if connected two wye.

88. What happens to the torque when the speed is changed from high to low? Why?

89. What happens to the horsepower when the speed is changed from high to low? Why?

90. Why does the torque remain constant in a constant-torque motor and the horsepower remain constant in a constant-horsepower motor?

91. Draw a straight-line diagram of a constant-horsepower winding using the colors as in question 86.

92. (a) Draw the A-phase, four-pole, one-delta, long-jumper motor showing the polarity. (b) Draw the A phase of a four- and eight-pole constant torque showing

the polarity if connected one delta. (c) Draw the A phase of a four- and eight-pole constant-horsepower motor showing the polarity if connected one delta. Which two-speed drawing resembles the delta connection?

93. What spot in each phase of the two-speed consequent-pole windings determines if it will be constant torque or constant horsepower?

94. How can the line-lead connections show the difference between constant torque or constant horsepower?

95. If a two-speed consequent-pole winding is used with another winding in the same stator, why should it be open when the other winding is energized?

96. Draw the A phase of a variable-torque motor.

97. What makes this connection different than that of a constant torque?

98. What is the advantage of winding a one-speed motor consequent-pole?

99. When is odd-pole grouping necessary?

100. Why must each phase have the same number of coils and turns?

101. What connections can have long jumper or short jumper when odd-pole grouping is used?

102. When are dead coils necessary?

103. Why is it necessary to install the dead coils? Why must the ends of the dead coils be insulated?

104. If a motor is connected 440 volts one wye, can it be reconnected for 220 volts?

105. If a motor is connected one wye, 220 volts, can it be reconnected to run on 440 volts?

106. If a 230-volt one delta is reconnected to one wye, what voltage would be needed to keep the volts per group the same as with one wye?

107. If a 440-volt, one-wye-connected motor is changed to one delta, what would be the right voltage for it?

108. Change a 230-volt, one-wye winding with 30 turns of No. 18 wire to a 460-volt, one-wye winding.

109. Will a 50 Hz motor run faster on 60 Hz?

110. Explain chord factor.

111. How many electrical degrees are in one pole?

112. What does each tooth within a pole have to do with chord factor?

113. What are the advantages of ball bearings over sleeve bearings?

114. What is the difference between a seal and a shield in a ball bearing?

115. Name the conditions that can shorten the life of a ball bearing.

116. When should a ball bearing be replaced?

117. What are some things that should be considered when choosing a replacement ball bearing?

118. What will happen to a ball bearing when there is misalignment of the end plates?

119. Name several methods used to install a ball bearing.

120. What can happen if too much grease is forced into a ball bearing?

121. How is a three-phase motor reversed?

122. What is a ground?

123. Why does the lead that is closer to the grounded coil show less resistance to the frame than the other leads?

124. Describe how to locate a ground.

125. Describe how to locate an open.
126. Define a short.
127. Describe how to locate the shorted circuit in a nine-lead, dual-voltage motor connected one wye.
128. What are the symptoms when a motor has a reversed coil group?
129. How does a test rotor show which group is reversed?
130. How does a test rotor show that a complete phase is reversed?
131. What are the symptoms of a motor that is single phasing?
132. (a) List and explain the troubles that may cause a three-phase motor to run excessively hot. (b) What effect will excessive heat have on the life of the insulation?

CHAPTER 4 STUDY QUESTIONS

1. (a) What is the function of a starter or controller? (b) Why is it necessary to have starters in most installations? (c) Name the main types of starters used for a-c motors.
2. (a) Explain what is meant by an "across-the-line" starter. (b) Name several applications for this type of starter. (c) What characteristics of the motors make it possible to use "across-the-line" starters?
3. (a) Why is it necessary to have reduced-voltage starters for some motors? (b) Give several specific applications where this type of starter would be necessary.
4. What is the difference between a line diagram and a wiring diagram?
5. (a) Show a simple diagram of a pushbutton switch starter and explain its operation. (b) For approximately what size motors are these starters used and why?
6. Explain the operation of (a) the solder pot overload relay, (b) the bimetallic overload relay. (c) What is meant by "trip free"?
7. How many overload relays are used on a three-phase full voltage starter?
8. (a) Explain the construction of the holding coil on a magnetic across-the-line starter. (b) Why is the shading coil needed?
9. What are the advantages of a magnetic across-the-line starter over a manual across-the-line starter?
10. (a) Describe the construction of a simple START-STOP pushbutton station. (b) Explain the operation of a station having four contacts.
11. (a) Explain how a START-STOP pushbutton station should be connected to a magnetic switch. (b) Show a diagram of this connection. (c) How many wires should there be between station and starter?
12. (a) Show by a diagram the connection for a START-STOP station to a magnetic switch to control a three-phase motor. (b) Explain the operation and trace out the circuit. (c) Where are the overload contacts located?
13. Show a diagram of a three-phase full-voltage starter with a step down transformer in the control circuit.
14. Explain the reaction of the starter if the maintaining contacts do not close when the START button is pressed.
15. (a) Connect two START-STOP stations to control a three-phase magnetic switch. (b) How are the maintaining contacts always connected? (c) How should the STOP buttons be connected? (d) How should the START buttons be connected?

16. (a) What is meant by jogging or inching a motor? (b) Give several applications where jogging is used.

17. (a) Draw a diagram of a three-phase magnetic starter connected to a station having a JOG button. (b) Explain the operation of the starter when the JOG button is pressed.

18. (a) What is the purpose of a pilot or indicating lamp on a START-STOP station? (b) Show where it is connected in the circuit.

19. (a) What is a reversing magnetic starter? (b) Give some applications for which a starter of this type is used.

20. (a) Explain the construction and operation of a reversing magnetic starter. (b) Show a diagram of this starter. Label all parts.

21. (a) Connect a magnetic-reversing, three-phase starter to a FORWARD-REVERSE-STOP station, and explain the circuits when each button is pressed. (b) What is likely to happen if the REVERSE button is pressed while the FORWARD contacts are in?

22. Give a specific example of how a mechanical interlock is used to prevent the FORWARD and REVERSE contacts from operating at the same instant.

23. (a) Draw a diagram of a reversing magnetic starter connected to FORWARD-REVERSE-STOP station having an electrical interlock. (b) Trace each circuit and explain how the interlock operates.

24. Give the names of several starters that start motors at a reduced voltage.

25. (a) What is a primary-resistance starter? (b) Describe the construction and operation of a primary-resistance starter of the manual type.

26. (a) Describe the construction and operation of a magnetic primary-resistance starter. (b) Connect this starter to a three-phase motor and explain the circuit when the START button is pressed.

27. (a) What is the purpose of the definite-time mechanism used on the magnetic primary-resistance starter? (b) How does it operate? (c) How is the time interval changed on these devices?

28. (a) Draw a diagram of a secondary-resistance starter and label all parts. (b) Explain its principle of operation.

29. (a) Show a three-phase slip-ring motor connected to a secondary-resistance starter. (b) Explain the circuit and operation. (c) Describe the construction of a three-phase slip-ring motor and its principle of operation.

30. (a) Show by diagram how a magnetic secondary-resistance starter is connected to a three-phase slip-ring motor. (b) Explain how the timing mechanism operates.

31. How does a solid-state, reduced-voltage starter control the current of the motor?

32. What two methods are used to control the time that current is limited before full current is applied?

33. Explain how the breakaway torque adjustment starts the motor.

34. What protective features are available with this control?

35. (a) What is a three-phase autotransformer starter? (b) What advantage does this starter have over a resistance starter?

36. (a) Diagram the construction and principle of operation of a three-phase compensator. (b) Why are three transformers used?

37. (a) Show a diagram of a three-phase compensator connected to a three-phase

motor. (b) Explain the sequence of operation. (c) What would happen if one transformer should open while the motor is running?

38. (a) Describe briefly a magnetic compensator, and explain its advantage over the manual type. (b) What is meant by closed transition?

39. (a) Explain the wye-delta method of reduced-voltage starting. (b) How many wires must be brought out of a motor started in this way? (c) What are these wires connected to inside the motor?

40. (a) Connect a three-phase motor so that it can be started wye and run delta. Use a three-pole double-throw switch. (b) Trace out and explain the circuit.

41. (a) Show a schematic diagram of an automatic wye-delta starter. (b) Explain its operation. (c) Where is this type of starter used?

42. (a) What is a part-winding starter? (b) Show a diagram of a part-winding starter connected to a nine-lead wye connected motor. (c) Describe the sequence of operation.

43. Show diagrams of a small drum switch operating a three-phase motor and a capacitor motor.

44. What connection features of the motor permit it to operate at different speeds?

45. (a) Connect a two-speed starter to a three-phase motor having two sets of windings. (b) Explain in detail the sequence of operation.

46. (a) Connect a two-speed starter to a three-phase motor having a consequent-pole winding.

47. Explain how the adjustable frequency controller changes the frequency.

48. Why should the voltage be changed when the frequency is changed?

49. Name and explain the features that these controllers can have.

50. (a) What is meant by "plugging" a three-phase motor? (b) How is this accomplished? (c) Why is plugging necessary in some applications?

51. (a) Show a diagram of a starter that uses a plugging relay. (b) Explain the operation of the relay and the entire circuit.

52. What procedure would you follow in locating the source of trouble if a motor does not start when the main contacts of an across-the-line starter close?

53. (a) What may be the trouble if the main contacts of a magnetic starter do not close when the START button is pressed? (b) Explain how you would remedy each problem.

54. What usually causes a fuse to blow or the overload relays to operate when the START button is pressed?

55. (a) List some other problems, besides those listed above, which may be encountered in automatic starters. (b) How would you remedy these faults?

56. What precaution should be taken before working on controls?

57. What is a symptom of a loose connection?

58. Where are overload contacts located in relation to the holding coil?

59. Where are the control devices located in relation to the holding coil?

CHAPTER 5 STUDY QUESTIONS

1. (a) Show by diagram the construction of a typical armature. Label all the parts. (b) How are the commutator and the laminations placed on the shaft?

2. (a) Name the operations involved in the process of armature winding. (b) Which operations in your opinion are more important than others?

3. (a) By means of simple schematic diagrams show how the coils in an armature are connected to the commutator. (b) How many commutator bars are necessary for an armature with nine coils? Why?

4. (a) Why is it necessary to insulate an armature before winding? (b) Where is the insulation placed? (c) Explain how the insulation should be cut so that the armature will be properly insulated.

5. (a) What is meant by pitch of a coil? loop winding? coil throw? (b) Diagram each.

6. Assume a small seven-slot armature and describe in detail the steps to be taken in winding this armature after it has been stripped.

7. (a) What is meant by lead swing? (b) Show the methods used in determining the position of the leads in the commutator. (c) Why is it necessary to put leads into the correct commutator bars? (d) What effect would an incorrect lead swing have on the operation of a motor?

8. (a) Explain why wedges are placed in each slot after the armature is wound. (b) Show by diagram how this is done. (c) What would happen if wedges were not placed in the slots?

9. (a) What is meant by a two-coil-per-slot winding? Show in a diagram. (b) In an armature of this type how many slots will there be if the commutator has 18 bars? 30 bars? (c) How many bars should the commutator have if there are 11 slots in the armature?

10. (a) Diagram and explain how you would wind a nine-slot, two-coil-per-slot armature. (b) How many loops will this winding have?

11. (a) Give the names of the two main types of armature windings. (b) In what way do they differ?

12. Define a simplex lap winding and draw a simple diagram of it.

13. (a) Explain how duplex and triplex lap windings differ from the simplex winding. (b) Show diagrams of these windings. (c) Which of these windings are most frequently used on small armatures? Why?

14. (a) What methods are used to identify adjacent loops in a two-coil-per-slot winding? (b) What is the reason for marking the leads?

15. Show by diagrams several coils of a simplex lap winding that does not have loops and explain how the leads are placed into the commutator bars.

16. (a) Show by diagram several coils of a two-in-hand simplex lap winding and explain how the leads are tested to determine their correct location in the commutator bars. (b) Do the same for a three-in-hand lap winding.

17. (a) What is the difference between a coil winding and a hand winding? (b) Why are these two types of winding used? (c) Can all armatures be hand wound?

18. What is the difference between a lap and a wave winding? Show diagrams of each. Why are some armatures lap wound and others wave wound?

19. Show a circular diagram of a one-coil-per-slot wave winding having 23 slots and a pitch of 1 and 7. Trace the winding through half the coils.

20. (a) What is meant by commutator pitch? (b) Give the formula for determining commutator pitch for a wave-wound armature. (c) Determine the pitch for a 59-bar four-pole armature.

21. (a) Explain the difference between a progressive and retrogressive winding. (b) What happens if progressive is changed to retrogressive?

22. (a) Explain what equalizer connections are and why all motors do not have them. (b) How do you determine the span of an equalizer connection?

23. What information should be recorded before an armature is rewound?

24. Show a typical data sheet.

25. (a) Describe how the position of the leads on the commutator may be recorded by marking the commutator and the slots of the armature. (b) Diagram this for a loop, lap, and wave winding.

26. (a) What precautions should be observed in stripping an armature? (b) Why should at least one coil of a coil-wound armature be saved during the stripping process?

27. (a) Explain how the leads are soldered in the commutator bars. (b) What precautions should be taken to prevent solder from flowing behind the commutator?

28. (a) What is the purpose of cord, tape, and wire bands on armatures? (b) Describe how cord, tape, and steel bands are placed on armatures.

29. (a) What is meant by a shorted commutator? (b) How is a commutator tested for short circuits? (c) At what point during the winding process should the commutator be tested for shorts?

30. (a) Give some of the causes of grounds in a winding. (b) Where do the grounds usually occur? (c) How is the winding tested for grounds?

31. (a) What is a growler? (b) How is a grounded coil located by means of a growler? (c) Explain the construction and operation of a growler.

32. (a) What is meant by a bar-to-bar meter test? (b) How is the winding connected to the line wires for such a test? (c) How is the amount of current flow to the winding controlled?

33. Explain how a grounded coil is removed from the circuit of a loop-, lap-, and wave-wound armature. (b) Why is it necessary to remove a grounded coil from the circuit? (c) Is it always possible to do this? (d) If not, what must be done?

34. (a) Explain why armatures should be balanced. (b) How is this done?

35. (a) Explain the purpose of baking and varnishing an armature. (b) When and how is this done?

36. (a) Show by diagram the growler hack-saw blade test for a shorted armature. (b) Why can't this test be used on an armature having equalizer connections?

37. (a) Show by diagram the bar-to-bar meter test for locating a shorted coil. (b) Describe how an armature can be tested for shorts by means of the growler-meter method.

38. (a) Under what conditions is it advisable to eliminate shorted coils from the armature circuit? (b) When is it not advisable? (c) Why is it not always possible to cut out a shorted coil?

39. (a) How does a shorted coil show itself in the operation of a motor? (b) Why is it not advisable to run a motor with a shorted coil for any length of time?

40. (a) In testing an armature for shorts how can you tell whether the short is in a coil or in the commutator? (b) How can you tell whether there is more than one short?

41. (a) Describe and show by a diagram the bar-to-bar meter test for locating an open in an armature. (b) What precautions must be taken with the meter in this test?

42. (a) How is an open coil located by means of a growler test? (b) In what way is this test different from that in question 41?

43. (a) Show by diagram the method of jumping out an open coil in a lap and wave winding. (b) Explain how you would jump out an open coil on six-pole wave winding.

44. (a) Describe the bar-to-bar test for a reversed coil in a loop winding. (b) How would you make this test using a growler?

45. (a) Describe how to test for reversed coils in a two-in-hand lap winding and wave winding. (b) How would you remedy this condition when it has been found?

46. Name the various parts of a commutator.

47. (a) Describe the construction and function of the commutator. (b) What material is the commutator bar made of? (c) Why must the bars be insulated from the rings?

48. (a) Explain how a commutator is disassembled preparatory to insulating it. (b) What information must be taken while it is being disassembled?

49. (a) What is a mica V ring? (b) Explain the three methods that can be used to make these rings. (c) Why must heat be used to shape the rings? (d) Can this be done without heating the mica?

50. (a) How can you eliminate a short between commutator bars that is due to carbonized mica? (b) What must be done if much scraping is necessary?

51. (a) Explain how two shorted bars can be reinsulated without disassembling the entire commutator. (b) How could you quickly make a repair if the bars could not be reinsulated?

52. Assuming that the entire commutator has to be reinsulated, how would you go about it when the commutator is connected to a good winding?

53. (a) What is meant by high bars? low bars? (b) What is their cause and how is it remedied?

54. (a) What is a commutator stone? (b) When is it used? (c) What precautions must be observed in using it? (d) Why can't sandpaper be used as a substitute?

55. (a) What is meant by high mica? (b) How is it caused and what is the remedy? (c) What effect will it have on the operation of a motor?

56. (a) What is meant by undercutting? (b) How is this done? (c) Why must this be done on certain commutators?

CHAPTER 6 STUDY QUESTIONS

1. (a) Name the main parts of a dc motor. (b) Describe the construction of each part and give the function of each.

2. What is the purpose of bearings in a motor?

3. (a) Show a simple drawing of a sleeve bearing and an oil ring. (b) What is the purpose of the oil ring? (c) How is oil conducted along the shaft resting in the bearing?

4. (a) What is meant by brush rigging? (b) Why is this movable on some motors and not on others? (c) Why are the brushes insulated from the end brackets?

5. Name four types of dc motors.

6. Describe the construction of the permanent-magnet motor.
7. What is the difference between the field windings of a series motor and a shunt motor?
8. Describe the path of magnetic lines of force in a dc stator.
9. What is the purpose of a commutator?
10. What is the purposes of the brushes?
11. What are three factors that govern the amount of voltage generated?
12. What direction does generated current flow compared to current being used as power in a motor?
13. When a generator is adding power to a line, what would happen if the generator-output voltage fell below that of the line voltage?
14. What would happen if a motor were pulled faster than its loaded speed?
15. What is counter electromotive force (e.m.f.)?
16. What effect does counter e.m.f. in an armature have on the current supplied by the line?
17. How does counter e.m.f. compare with a battery being charged?
18. How does counter e.m.f. control the speed of an armature?
19. What would happen to an armature if counter e.m.f. were eliminated?
20. Explain what happens when the voltage supplying the armature is reduced.
21. What happens when the voltage applied to the shunt field is reduced?
22. How is the speed of a permanent magnet motor controlled?
23. What happens to the speed of a permanent-magnet motor when the magnet becomes weak? What will happen to the armature?
24. What can cause the permanent magnet to become weak?
25. (a) Draw a schematic of a shunt motor. (b) How can the speed of a shunt motor be varied? (c) What will cause the speed to increase?
26. Where is the most power used in all dc motors?
27. In which circuit should the overspeed or torque control be located?
28. In which circuit is the underspeed or horsepower control located?
29. What is the danger in operating a motor too slowly for a long time?
30. Why doesn't a shunt motor work very well with a varying load?
31. Draw a schematic of a series motor.
32. What limits the current of the series field when a series motor is running?
33. What happens to the lines of force from the series field when a series motor accelerates?
34. What limits the speed of a series motor?
35. Why doesn't the back e.m.f. limit the speed of a series motor?
36. Draw a schematic of a compound motor.
37. Describe the construction of a compound motor.
38. How does the series field strengthen the motor when the load slows the armature?
39. What is the difference between a stabilized shunt motor and a compound motor?
40. (a) Describe the method used for winding series-field coils. (b) What is the general construction of the series-field coil?
41. (a) Describe in detail how a compound-field coil is wound. (b) Make a diagram of this coil. (c) What precautions must be taken when winding it?

42. (a) What is an interpole field? (b) How is it wound? (c) Why is heavy wire used in its construction?
43. (a) What is the rule for connecting field poles for proper polarity? (b) What effect would improper polarity have on the operation of a motor? Diagram the field-coil connection of a two-pole motor having correct polarity.
44. Describe three methods for testing coils to determine if they have correct polarity.
45. How would you test for correct field-coil polarity while the motor is completely assembled?
46. Show a diagram of the connections of a series motor. (b) Trace out and explain the circuit. (c) What characteristics of the series motor make it dangerous to run this motor without a load?
47. (a) Make a diagram of a shunt motor. (b) Explain the circuit and trace out the connections.
48. (a) Draw a diagram of a two-pole compound motor. (b) Show arrows on all connecting wires to indicate the direction of current flow in the field poles.
49. Name four different types of compound motors in general use.
50. Define the following: (a) cumulative; (b) differential; (c) long shunt; (d) short shunt.
51. Draw the following diagrams: (a) two-pole, long-shunt cumulative motor; (b) two-pole, long-shunt differential motor; (c) two-pole, short-shunt cumulative motor; (d) two-pole, short-shunt differential motor.
52. What is an interpole? What purpose does it serve in a motor? How many interpoles are there in a four-pole motor?
53. (a) What is the rule for interpole polarity? (b) What two factors govern interpole polarity?
54. Draw the poles of a two-pole interpole motor showing the polarity of all the poles, assuming main pole polarity and counterclockwise rotation.
55. Draw a simple diagram showing how interpoles are connected in a motor.
56. Draw the same diagram as in question 54 for a four-pole interpole motor.
57. (a) Describe the procedure for connecting a two-pole, cumulatively connected, compound-interpole motor for a proper polarity, assuming main pole polarity and counterclockwise rotation. (b) Diagram to show the direction of current in each field coil.
58. (a) How is the direction of rotation of any dc motor reversed? (b) How is a series motor reversed? (c) Diagram to show how a series motor is reversed.
59. (a) Show by diagram how an interpole motor is reversed (b) What precautions must be taken in reversing an interpole motor?
60. Draw a diagram of a six-pole compound-interpole machine showing the polarity of all the poles and show how this motor is reversed.
61. List some of the tests that should be given to a motor before it is installed.
62. Explain and diagram the procedure for making a ground test on a motor. What can cause a field coil to ground?
63. Explain and draw a diagram showing how a shunt motor is reversed.
64. (a) Show by means of a diagram where grounds in a field coil are most likely to occur. (b) When a ground is indicated in the field of an eight-pole motor, show

how to find the coil in which the ground is located. (c) What would happen if the series and shunt field of a compound motor were grounded?

65. (a) What is meant by an open circuit in a motor? (b) Explain by diagram how series motors are tested for open circuits. (c) What may be the causes for open circuits in this motor?

66. (a) How are shunt motors tested for open circuits? Where are these opens usually located? (b) What would happen if the field should open while the motor is running? when the motor is started?

67. (a) What markings are usually put on the leads of a compound motor? (b) Why are these markings necessary?

68. (a) How are the six leads of a compound motor identified when the markings are missing? (b) Give the procedure in making this test.

69. (a) How are the leads of a compound motor identified when only five wires are brought out of the motor? (b) Will it be necessary to open the motor for this test?

70. (a) Give the steps in testing a compound motor to determine whether it is connected cumulatively or differentially. (b) What difference will it make in the operation of a motor?

71. (a) Describe a practical test to determine correct interpole polarity. (b) How would wrong interpole polarity show up in the operation of a motor?

72. (a) Describe one method of properly locating the brush holders in the neutral position for an interpole motor and a noninterpole motor. (b) Why will the wrong location cause the armature to spark?

73. (a) Describe three other methods for setting the brushes on netural. (b) Which of these methods would you use? Why?

74. (a) With what pressure should carbon brushes press against the commutator? (b) How is this pressure measured? (c) What effect will improper pressure have on the operation of the motor?

75. (a) How are the brushes made to fit the curvature of the commutator? (b) Why are different grades of brushes used on different motors?

76. (a) What are some of the causes of open circuits in the armature circuit of a dc motor? (b) Explain how to locate the open.

77. (a) What is meant by a motor "running away"? (b) What is the usual cause of this and how can it be prevented?

78. (a) What are some of the symptoms of a shorted armature in the operation of a motor? (b) What will the consequences be if a motor is allowed to run this way?

79. (a) Assuming that a motor with one or two shorted coils had to be put into operation very quickly, what would you do? (b) What would you do if two or more commutator bars were shorted?

80. (a) How does an open armature coil manifest itself while the motor is running? (b) How can you locate the open by inspecting the commutator?

81. (a) Name some of the conditions that may cause armature opens and explain how you would effect a repair. (b) How would you know that the open is repaired?

82. What is the importance of the nameplate data on a motor?

83. Explain in detail why a shunt motor will tend to race when the shunt field is opened.

84. Explain why a series motor must always run with a load.

85. (a) What are some of the reasons for sparking at the commutator? (b) Explain why each of these causes produces sparking and give the remedy for each.

86. (a) Why will incorrect lead swing cause sparking at the brush? (b) What other effect will this have on the motor?

87. (a) What are the symptoms of a motor running with wrong interpole polarity? (b) How can you tell that these symptoms are due to wrong interpole polarity?

88. (a) What is meant by high bars? low bars? (b) To what are these conditions due and how are they remedied?

89. Describe some of the defects that may cause a motor to run noisily.

CHAPTER 7 STUDY QUESTIONS

1. (a) Name some of the functions of a starting box and controller. (b) What is the difference between the two? (c) Why is it necessary to use these devices?

2. Explain why a small motor can be started by placing full voltage across it while large motors must be started with reduced voltage. What will be damaged in a large motor?

3. (a) Describe the construction and operation of a three-point starting box. (b) Draw a diagram of all its internal connections and label all parts. (c) Why is it called a three-point box?

4. (a) Why is the holding coil of a three-point box called a no-field release? (b) What is the function of the holding coil? (c) How are the terminals of the box marked?

5. (a) Show a diagram of a three-point starting box connected to a compound motor. (b) Explain this circuit.

6. (a) Describe the construction and operation of a four-point starting box. (b) Draw a diagram of the internal connections of this box. Label all parts.

7. (a) Why is the starting box in question 6 called a four-point starting box? (b) What are some of the essential differences between a three-point and a four-point starting box? (c) What are the reasons for using a three-point box on some applications and a four-point box on others?

8. (a) What is the function of the holding coil on a four-point box? (b) Why is this coil called a no-voltage release coil?

9. (a) Draw a diagram of a four-point starting box connected to a shunt motor; to a compound motor. (b) Explain the circuit.

10. (a) What is a speed-regulating rheostat? (b) Make a connection diagram of a four-point, speed-regulating rheostat. (c) Describe its operation. (d) Where would you use a rheostat of this kind?

11. (a) What is meant by a combination four-point starting box and speed-regulating rheostat? (b) Show by means of a diagram the internal wiring of this device and explain fully how it operates. Label and describe its various parts.

12. Connect the box in question 11 to a compound motor and describe in detail all of the circuits involved.

13. (a) How is the direction of rotation of a dc motor changed? (b) Name several applications where the motor reverses periodically.

14. Connect a double-pole, double-throw switch in (a) the armature circuit of a shunt motor and (b) in the field circuit of a shunt motor. In both instances explain the circuits.

15. (a) Draw a diagram of a two-pole, compound-interpole motor with a double-pole, double-throw switch connected in the armature circuit for reversing. (b) What precaution must be taken in reversing this motor?

16. By means of a double-pole, double-throw switch, reverse a shunt motor connected to a three-point starting box. Explain exactly how you would start and stop this motor.

17. Draw a diagram of a four-point starting box connected (a) to a shunt motor and use a double-pole, double-throw switch for reversing; (b) to a compound motor and use a double-pole, double-throw switch for reversing.

18. (a) Show a sketch of the external appearance and internal construction of a small drum-type switch. (b) Show all contacts, label all parts, and explain the operation. (c) What is this switch used for?

19. (a) Show by diagram the connection of a series motor to a drum switch and the contacts for forward rotation. (b) Explain the circuit. (c) Show another diagram for reverse rotation.

20. (a) What is an overload relay? (b) What are several devices that can be used to protect a motor from overloads. (c) How can you tell that a motor is overloaded?

21. (a) Show a simple sketch of a magnetic circuit breaker and explain its construction and operation. (b) Why is this device used?

22. (a) Explain the construction and operation of a thermal relay. (b) What is the difference between a thermal relay and an overload relay? (c) What troubles can develop on a thermal relay?

23. Explain what is meant by a pushbutton station and show a sketch of a station having a START-STOP button.

24. (a) Draw a diagram of a magnetic switch and small dc motor connected to a START-STOP pushbutton station. (b) Show an elementary diagram of this connection.

25. (a) Show the same diagram as in question 24, but with two START-STOP stations. (b) Show the connection with three stations. (c) How should the STOP button always be connected?

26. (a) What may be the source of the trouble when the magnetic switch does not operate after pressing the START button? (b) Explain.

27. Explain what may be the trouble when the magnetic switch does not stay closed when the finger is removed from the START button.

28. What is the purpose of using several START-STOP stations to operate one magnetic switch?

29. (a) Explain the use of a JOG or INCH button in a pushbutton station. (b) Show all the contacts in a station having a START, a JOG, and a STOP button.

30. (a) Draw a diagram of a START-JOG-STOP station connected to a magnetic switch to operate a small motor. (b) Explain the circuits when each button is pressed. (c) Show one elementary diagram of this connection.

31. (a) What may be the trouble if the magnetic switch does not operate when the JOG button is pressed?

32. (a) Why is resistance needed in the motor circuit in order to start a medium-sized or large-sized motor? (b) What will happen if the motor is started without resistance?

33. List five different types of automatic controllers generally used for the control of medium-sized and large-sized dc motors.

34. (a) Explain the principle of the counter electromotive force controller. (b) Give an application of this controller.

35. (a) Show a diagram of a counter electromotive force controller with one step of resistance connected to a compound motor. (b) Explain the operation of this circuit.

36. (a) What is a lockout controller? (b) Why is it called by this name? (c) Why is it also known as current-limit starter? (d) Where would this type of controller be used?

37. (a) Connect a two-coil lockout controller with one step of resistance to a compound motor. (b) Explain the operation of the circuit.

38. Show in a diagram a two-coil lockout controller with two steps of resistance connected to a compound motor. Show the complete circuit with magnetic switch and START-STOP station.

39. (a) Diagram a single-coil lockout contactor. (b) Explain the principle of operation of this contactor. (c) What is the difference between this and the two-coil lockout contactor?

40. (a) Draw a wiring diagram of a single-coil lockout controller with one step of resistance connected to a compound motor. (b) Explain the operation.

41. (a) What is meant by a definite magnetic time controller? (b) Explain the principle of operation of this type of controller. (c) Diagram one of these controllers and label the parts.

42. (a) Draw a diagram and explain the circuit of a definite magnetic time starter connected to a compound motor. (b) Show also an elementary diagram of this starter.

43. (a) What advantages does this starter have over the lockout type of starter? (b) Why do you consider these advantages?

44. (a) Show a simplified diagram of a definite magnetic time starter having two steps of resistance. (b) For what applications would this starter be used?

45. (a) Show in a diagram what is meant by dynamic braking. (b) Why is dynamic braking needed in many instances? (c) Give several instances where it is necessary.

46. Draw a diagram of a definite magnetic time controller equipped with dynamic braking.

47. List and explain as many troubles as you can which may cause a definite magnetic time starter to function improperly.

48. Explain the difference between a definite magnetic time starter and a definite mechanical time starter.

49. (a) Describe by means of a diagram a definite mechanical time controller using dashpot acceleration and explain the operation. (b) Explain the operation of a dashpot.

50. (a) What are some of the things that may go wrong with the controller of question 49? (b) Explain each trouble and the remedy for it.

51. Show a typical diagram of a simple type of drum controller and describe the

circuit when the handle is at the first point of acceleration. Assume this controller is used with a compound motor.

52. Draw a straight-line diagram of a reduced voltage starter with time limit acceleration. Explain its operation.

53. Draw a straight-line diagram of an adjustable speed starter using a field accelerating relay. Explain the operation of the field accelerating relay.

54. What is ripple effect?

55. What are the two types of circuitry in an electronic controller?

56. Name five of the functions the control or regulatory circuit can perform.

57. Why does the three-phase controller develop a smoother dc than a single-phase controller?

CHAPTER 8 STUDY QUESTIONS

1. What is a universal motor? Name some of its characteristics and applications.

2. (a) Name and describe the main parts of a universal motor. (b) Show simple sketches of each part.

3. (a) Explain the operation of a universal motor. (b) What characteristics of construction make it possible to operate on either alternating or direct current?

4. What procedure should be followed when it is necessary to rewind the field coils of a universal motor?

5. (a) Explain how to make a form for winding field coils. (b) How are the right measurements for making the form obtained? (c) What would happen if the form were made too small? too large?

6. (a) Prepare a diagram to show how the field coils are connected and tested for correct polarity. (b) Why wouldn't a universal motor run if both fields of a two-pole motor were connected for like polarity?

7. (a) Show in a diagram how the field coils and armature are connected in a two-pole universal motor. (b) Is this the only way they can be connected?

8. (a) Show by diagram how to reverse the direction of rotation of a universal motor. (b) Is it always necessary to take the motor apart to reverse it? Explain.

9. (a) Why does severe sparking generally occur when the rotation is reversed on some types of universal motors? (b) How can the sparking be eliminated?

10. Name and explain some important features that are common to all universal motors.

11. (a) What information must be recorded before an armature can be rewound? (b) Draw a chart with a sample recording. (c) What might be the result if the wrong information is recorded?

12. (a) Describe in detail how to determine the correct lead throw on a small armature. (b) What would happen if the armature was rewound with wrong lead throw?

13. (a) Describe how to determine correct lead throw by using a growler. (b) What are some other functions of a growler?

14. (a) How must an armature be prepared before it is ready for winding?

(b) Describe briefly the method of rewinding the armature of a universal motor.

15. (a) What differences will sometimes be found in the windings on the armature of a universal motor? (b) Show some of these differences by means of sketches. (c) How do these differences affect the operation of the motor?

16. (a) What precautions should be taken with respect to the position of the leads in the commutator? (b) What would happen if the leads are placed one or more bars out of the way?

17. (a) What is meant by a compensated universal motor? (b) Describe the single-field compensated universal motor.

18. (a) Describe the two-field compensated universal motor. (b) What function does the compensating field serve in this motor?

19. (a) What precautions should be taken when stripping the stator of a compensated universal motor? (b) List all the information that should be recorded.

20. (a) Describe briefly how the stator of a compensated universal motor is rewound. (b) Why is the compensating winding located 90 electrical degrees from the main winding?

21. (a) List and explain as many methods as you can to show how the speed of a universal motor can be varied and regulated. (b) What applications do you know of for universal motors that can be varied in speed.

22. Diagram and explain the layout of the coils of a two-field compensated universal stator having 4 poles and 24 slots.

23. Show by diagram how the speed of a universal motor may be regulated by using a variable resistance in the motor circuit.

24. (a) How may different speeds be obtained by tapping one field of a universal motor? (b) Explain the principle of operation of this type of speed control.

25. Explain how speed may be controlled by means of a centrifugal device.

26. (a) What are some of the troubles that may cause a universal motor to spark excessively? (b) Explain and give a remedy for each trouble.

27. List as many troubles as you can that may cause the universal motor to (a) run hot; (b) to smoke; (c) to have poor torque.

28. When a universal motor runs slower than it should, it is an almost certain sign that it is defective. Explain how you would diagnose the trouble of such a motor and repair it.

29. (a) Give a simple definition of a shaded-pole motor. (b) List some of its characteristics and applications.

30. Name and illustrate the main parts of a shaded-pole motor and explain the function of each.

31. (a) Explain the principle of operation of a shaded-pole motor. (b) What is the purpose of the shaded coil? What will happen to the operation if the shading coil opens?

32. (a) Show a connection diagram of a six-pole shaded-pole motor. (b) How do you test for correct polarity? (c) Why isn't it necessary for the shaded coils to be insulated from ground?

33. (a) What precautions should be taken in rewinding the field coils of shaded-pole motors? (b) Some shaded-pole motors have an iron bridge between pole pieces. What is this for?

34. (a) Show by diagram how a shaded-pole motor is reversed. (b) How can you tell just by looking at the stator in which direction the motor will rotate?

35. (a) Describe and make a diagram of a shaded-pole motor that can be reversed by means of external leads. (b) Explain the operation of this motor.

36. (a) Describe and make a diagram of a reversible shaded-pole motor that has two main windings and one shaded-coil winding. (b) How many leads are brought out of this motor?

37. (a) What may be some of the reasons for a shaded-pole motor failing to start? (b) Why is it particularly important that the bearings of a shaded-pole motor be in perfect condition?

38. (a) Explain how a shaded-pole motor is tested for grounds, short circuits, opens. (b) Describe how you locate and eliminate all of these defects.

39. List the possible troubles of a shaded-pole motor when it runs too hot; when it has very poor starting torque.

40. (a) Make a connection diagram of a two-speed, split-phase fan motor having two running windings and one starting winding. (b) How many leads are brought out of this motor? (c) How can you tell which is the correct lead for connecting?

41. (a) Explain and show a diagram of a three-speed split-phase fan motor having one running, one starting, and one auxiliary winding. (b) Explain the principle involved in the speed control of this motor.

42. (a) Show by diagram the connections of a two-speed split-phase motor having one running and one starting winding. (b) Explain how two different speeds are obtained from this motor. (c) Explain the principle of consequent connections.

43. (a) How is a universal motor controlled for changes in speed? (b) What would happen if a field coil on this motor should open while the motor is running?

44. Many split-phase fan motors have a transformer in the base of the stand to control the speed. Show by means of a diagram how this transformer is connected to the motor.

45. Many fans are driven by capacitor motors and are controlled for speed by means of a transformer, as in the case of the motor in question 44. Show how three different speeds can be obtained from this connection.

46. (a) With a diagram show how a fan motor used on unit heaters is connected for different speeds. (b) Explain the principle involved in its operation.

47. Explain with a diagram how the speed of a shaded-pole motor is varied.

CHAPTER 9 STUDY QUESTIONS

1. What is the difference between a motor and a generator?

2. How are dc generators rated?

3. (a) Describe the construction of a dc generator. (b) How does it differ from that of a dc motor?

4. What happens when a conductor cuts magnetic lines of force?

5. What factors will cause a change in the amounts of voltage generated in a dc generator?

6. Explain how the direction of the generated voltage can be changed.

7. What are the three essentials necessary to cause a voltage to be generated?

8. Name three ways of producing the flux necessary in the generation of electricity.

9. What is meant by a separately excited generator? a self-excited generator?
10. (a) Explain in detail the operation of a self-excited generator. (b) Explain what is meant by the "building-up process."
11. (a) Explain with a diagram the connection and operation of a self-excited series generator. (b) What happens to the generated voltage when load is added or taken away?
12. (a) Show a diagram of a self-excited, shunt generator and explain its operation. (b) What are the characteristics of this generator?
13. (a) Describe the most common type of compound generator. (b) Show a diagram of this generator and describe its operation.
14. (a) What is meant by an over-compounded generator? flat-compounded generator? under-compounded generator? (b) Describe the characteristics and uses of each.
15. (a) How does the polarity rule of interpoles in a dc generator differ from that of a dc motor? (b) Show simple illustrations of each.
16. Diagram to show the connection of a four-pole compound-interpole generator.
17. Explain how reversed interpole polarity would affect the operation of an interpole generator.
18. How does direction of rotation affect the operation of a dc generator?
19. It is necessary sometimes to change a compound motor to a compound generator. Show with a diagram how this is accomplished.
20. (a) What kind of device is used to regulate the voltage generated? (b) How is it connected in the circuit? Explain how it is used in the circuit.
21. (a) Show by diagram how an ammeter and a voltmeter are connected in a generator circuit. (b) What is an ammeter shunt?
22. What is meant by paralleling generators and why is it done?
23. In order to connect two generators in parallel, what three conditions are necessary?
24. (a) What is an equalizer connection? (b) What is the reason for having this when two generators are paralleled?
25. Draw a diagram of two compound generators in parallel.
26. (a) If a generator refused to generate, what troubles would you suspect? (b) How would you remedy them?
27. Why would wrong field-pole connections prevent a generator from building up?
28. What would cause the generated voltage to drop if a load is added to a generator?
29. (a) What may be some of the troubles if the voltage does not build up completely? (b) How do you proceed to locate the fault?
30. (a) How is the neutral point of the brushes located in a compound-interpole generator? (b) How would you know that you have the correct position?
31. (a) What would cause the armature to spark while the generator is operating? (b) Give remedies for each of the troubles.
32. How would you define a synchronous motor?
33. What are some of the characteristics and uses of a synchronous motor?
34. (a) Describe and diagram the construction of a synchronous motor. (b) What methods are used to excite it?

35. (a) What is an amortisseur winding? (b) What purpose does it serve? (c) In what type of motor is it used?

36. (a) Explain how you would start a synchronous motor. (b) Explain how the magnetic poles on the motor lock in with the rotating magnetic field.

37. Explain how the stator of a synchronous motor is wound and how the rotor is wound.

38. Show a complete connection diagram of a synchronous motor having external excitation.

39. (a) Describe the construction of a synchronous motor with a rotor that is not externally excited. (b) Explain its operation. (c) What happens if you overexcite or underexcite the rotor field?

40. (a) Draw a diagram showing the internal connections of a brushless synchronous motor. (b) Explain its operation.

41. (a) What types of motors do electric clocks use? (b) Describe two of these types and explain their operation.

42. What problems are usually encountered on clock motors and how are these troubles remedied?

43. How does a synchronous generator differ from a synchronous motor?

44. Show a complete wiring diagram of a synchronous generator and explain its operation.

45. What effect will varying the exciting currents have on a synchronous generator?

46. Name and explain the conditions that must be satisfied when alternators are paralleled.

47. Draw an elementary diagram of a brushless synchronous generator and explain its operation.

48. Explain with diagram the "all dark" and "one dark and two bright" methods of synchronizing two alternators.

49. What would happen if the synchronizing switch is closed when the lamps of the "all dark" method are not entirely dark?

50. (a) Explain what is meant by a "synchro." (b) Explain its use and characteristics.

51. (a) In what way does a synchro resemble a synchronous generator? (b) How do they differ? (c) Describe the construction of the synchro and show a simple diagram of the windings.

52. (a) How does a synchro operate? (b) Draw a diagram of two synchros, one of which is the transmitter and one the receiver. (c) Trace out and describe in detail the function of each.

53. What effects would two reversed-phase wires have on the operation of the synchros?

54. Describe the stator and rotor windings of a wound-rotor, three-phase motor.

55. Name the connections that are found on the rotor of a wound-rotor, three-phase motor.

56. Where does the rotor voltage come from?

57. What is the purpose of the slip rings?

58. What effect does a reduction of rotor amps have on the shaft speed?

59. What is meant by poor speed regulation?

60. What actually controls the speed of the shaft?

61. Can all wound-rotor motors be started without resistance in the rotor circuit?
62. Why is there more inductive reactance in a wound rotor than in a squirrel-cage rotor?
63. What is the result of a good phase angle?
64. What is the advantage of a regenerative electronic controller?
65. What are some of the problems that can occur in a wound rotor?

CHAPTER 10 STUDY QUESTIONS

1. How are all substances classified in terms of electrical conductivity?
2. What elements are mainly used in the manufacture of semiconductor devices?
3. (a) Describe the Bohr model of an atom. (b) What charges do the atomic particles carry?
4. How does the Bohr model differ from the real atom?
5. What is meant by a valence electron?
6. Describe the modes of current flow in semiconductors.
7. (a) Why are impurities added to pure silicon or germanium? (b) Define doping.
8. (a) What is meant by covalent bonding? (b) Define N-type and P-type semiconductors.
9. Define hole as applied to the crystal structure of a semiconductor.
10. (a) Describe a P-N diode using an illustration. (b) Label all parts and describe the depletion region.
11. What is meant by reverse and forward bias?
12. Show a symbol of a diode, and label its parts.
13. (a) Define a diode rectifier. (b) Show current flow when a diode rectifier is connected to a dc source.
14. By means of a characteristic curve, explain the operation of a diode.
15. Describe the operation of a half-wave rectifier.
16. (a) What is meant by filtered dc? (b) Show a diagram using a capacitor for filtering purposes.
17. (a) In what way does full-wave rectification differ from half-wave rectification? (b) Show a full-wave rectifier using a center-tapped transformer and (c) using a bridge rectifier. (d) How would you filter these circuits?
18. (a) What is a zener diode? (b) Show the symbol for this diode and its characteristic curve.
19. Show a circuit in which a zener diode is used for voltage regulation.
20. Illustrate the operation of a transistor amplifier.
21. Illustrate the NPN and PNP transistors and label the terminals.
22. (a) What is the function of each element in the transistor? (b) Why is the emitter-base circuit forward biased? (c) Why is the collector circuit reverse-biased?
23. Describe the function of each transistor configuration. Draw the circuit of each.
24. Explain how the common emitter amplifier gives both current and voltage gain.

25. (a) What is an SCR? (b) Show a symbol for the SCR and label the terminals. (c) Describe its construction and function.

26. (a) By means of a curve, describe the characteristics of an SCR. (b) Define holding current, blocking state, forward breakover voltage, and reverse breakdown voltage.

27. Explain the operation of an SCR, assuming the SCR as two transistors, a PNP and NPN. Illustrate.

28. List at least six important factors in the operation of SCRs.

29. What is meant by a control or trigger signal?

30. Describe the structure of a triac and explain its operation.

31. What limits the triac's upper operating frequency?

32. What is the function of a trigger circuit?

33. (a) Describe the construction and operation of the unijunction transistor. (b) Show the symbol for the UJT and label all its parts.

34. Show a diagram of a UJT used in a relaxation oscillator circuit arrangement and trace its circuit.

35. Describe the structure and operation of the PUT.

36. What are the advantages of the PUT over the UJT?

37. Describe the structure and operation of the SUS.

38. Compare the output capabilities of the UJT, PUT, and SUS.

39. Describe the structure and operation of the diac.

40. (a) Explain the meaning of phase control. (b) Illustrate half-wave phase control.

41. By means of illustrations, discuss full-wave phase control.

42. (a) Explain the term *resistance triggering*. (b) Show how this type of triggering is used with a constant resistance and a variable resistance.

43. Draw a diagram in which a capacitor is used in conjunction with a variable resistor in order to trigger the SCR.

44. In indirect *RC* triggering how are the capacitor charging and discharging times computed.

45. Show diagrams and explain the operation of half-wave and full-wave circuits using the unijunction transistor for triggering purposes.

46. Draw a diagram and explain how a transistor can be used in place of a variable resistor in order to charge a capacitor.

47. Explain the function of the zener diode in Figure 10-55.

48. What precautions must be observed in applying phase control to motors?

49. (a) Define reference signals and feedback signals. (b) Show a circuit explaining reference and feedback voltages.

50. (a) What is meant by counter electromotive force? (b) How is counter e.m.f. used as a feedback signal?

51. (a) Draw an elementary diagram of a universal motor connected for half-wave control with feedback. Explain its operation. (b) What are some of the disadvantages of this circuit?

52. How may the circuit of question 51 be improved in terms of a shorter conduction time for the SCR? Show this diagram.

53. Show a half-wave control circuit with feedback in which a zener diode is used for supplying a constant potential.

54. Draw a diagram of a half-wave universal motor control in which the field

and armature do not have separate connections. Explain its operation and why this circuit is an improvement over that of question 51.

55. Why is it unnecessary to separate the field and the armature in the circuit of question 54?

56. Describe the effects of the slope of the trigger voltage on an SCR's firing stability.

57. What are the advantages of indirect triggering over direct triggering?

58. (a) Diagram a full-wave dc control circuit that has separate connections for the series field and armature. (b) In what way is the circuit an improvement over the half-wave circuit?

59. Define precise triggering. How is it obtained?

60. (a) Draw an elementary diagram of a half-wave control for a shunt motor. (b) Explain how the shunt field is supplied with a continuous unidirectional current.

61. (a) Explain what is meant by a commutating diode. (b) What is its function?

62. (a) Show a diagram of a full-wave, speed-controlled, shunt-wound, dc motor. Label each component and explain its function.

63. Explain why the speed of induction motors is more readily controlled by variable-frequency drives than by voltage control.

64. Why must a tachometer be used to obtain feedback data for an induction motor?

65. Draw a block diagram of a system using an induction motor to move a fluid at a constant speed.

66. How are SCRs protected against reverse voltages?

67. Describe the operation of the protective devices in Figure 10-75.

68. Explain why the transistor is a constant current source. Draw the voltage across a capacitor charged by such a source.

69. (a) How may the centrifugal switch of a split-phase or capacitor motor be replaced by a solid-state switch? (b) Explain how such a circuit operates.

70. Name and briefly explain several types of drives used for a three-phase supply.

71. Show an elementary power circuit of a magnetic drive, and describe its operation.

72. Show how pulse-width modulation determines a dc output.

73. Describe the operation of a Jones chopper.

74. What is the difference between a chopper and an inverter?

75. Why are inverters required to drive an ac motor?

76. Describe the operation of Figure 10-85.

77. Describe the operation of a cycloconverter. Why must its output frequency be less than its supply frequency?

78. What is a microprocessor? What is a microcomputer? How do the two differ?

79. Design a stepper motor to provide 15° steps.

80. Design a mechanical system using a stepper motor, to position a device at one-inch increments.

81. Change the welding machine program so that eight equally-spaced welds are made instead of six.

82. Explain the function of each box in Figure 10-92.

83. What is the function of a digital-to-analog converter?

84. How is pulse-width modulation used in a dc servo system?

INDEX

ELECTRIC

MOTOR REPAIR

THIRD EDITION

TEXT

APPENDIX

STUDY QUESTIONS

three-phase motors has been extensively revised and includes numerous new diagrams and information. The solid state chapter has been revised to include modern solid state material, as well as numerous types of semiconductors such as diodes, transistors, triacs, and SCRs. All chapters, including study questions, have been updated. In addition, ac and dc theories have been simplified and single-speed and, in particular, two-speed diagrams have been clarified.

Study questions for each chapter are arranged to follow the text material and sequence of information. These questions are valuable for the instructor, as well as for the student.

The last but by no means least feature of the book is its physical design—a design that permits text and related illustrations to be exposed simultaneously, that enables the reader to locate any desired illustration instantly, that allows the open book to be flat on the bench or desk, and that utilizes type large enough to be easily readable from the bench while the repair technician is working on a motor. Even the cover material and the special paper inside the book were selected for their unusual sturdiness and resistance to soiling under workshop conditions.

We welcome this opportunity to express our sincere thanks to our colleagues and associates for their suggestions and help, and to the many companies who have supplied much of the material, diagrams, and photographs used in this book.

Robert Rosenberg
August Hand

ELECTRIC MOTOR REPAIR

THIRD EDITION

ILLUSTRATIONS

Preface

For many years there has been a need for an intensely practical nontheoretical book on electric motor repair and control that could be used by people with little background of electrical knowledge. This has been only too evident in our contacts with workers over a period of many years in motor repair shops and with students during our years as instructors in motor repair and control in vocational, trade, and technical schools. It is with the hope of satisfying this pressing need that this book has been written. Inclusion of more than 900 illustrative drawings should make it particularly valuable as a direct working guide not only to the student, but to the repair technician at the bench as well.

Because the troubleshooter and repair technician must learn to do satisfactory work in the shortest possible time, we have tried to point out the best and quickest methods for testing and repairing. The heading Troubleshooting and Repair at the end of each chapter should be especially helpful.

Both alternating and direct current motors are treated thoroughly, and extensive consideration is given to the connections and troubles in controllers.

The contents of the third edition reflect to some degree requests and suggestions from students, electric motor repair technicians, and teachers who have used the second edition of ELECTRIC MOTOR REPAIR. Although numerous changes and additions of subject matter and illustrations have been made in the third edition, every effort has been made to preserve the character and objectives of the second edition. The chapters on the split-phase motors and the capacitor motors have been combined because of their similarity. More information on sine wave and inductive and capacitive reactance has been added. The chapter on

ELECTRIC MOTOR REPAIR

THIRD EDITION

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CHAPTER 1

Capacitor Motors

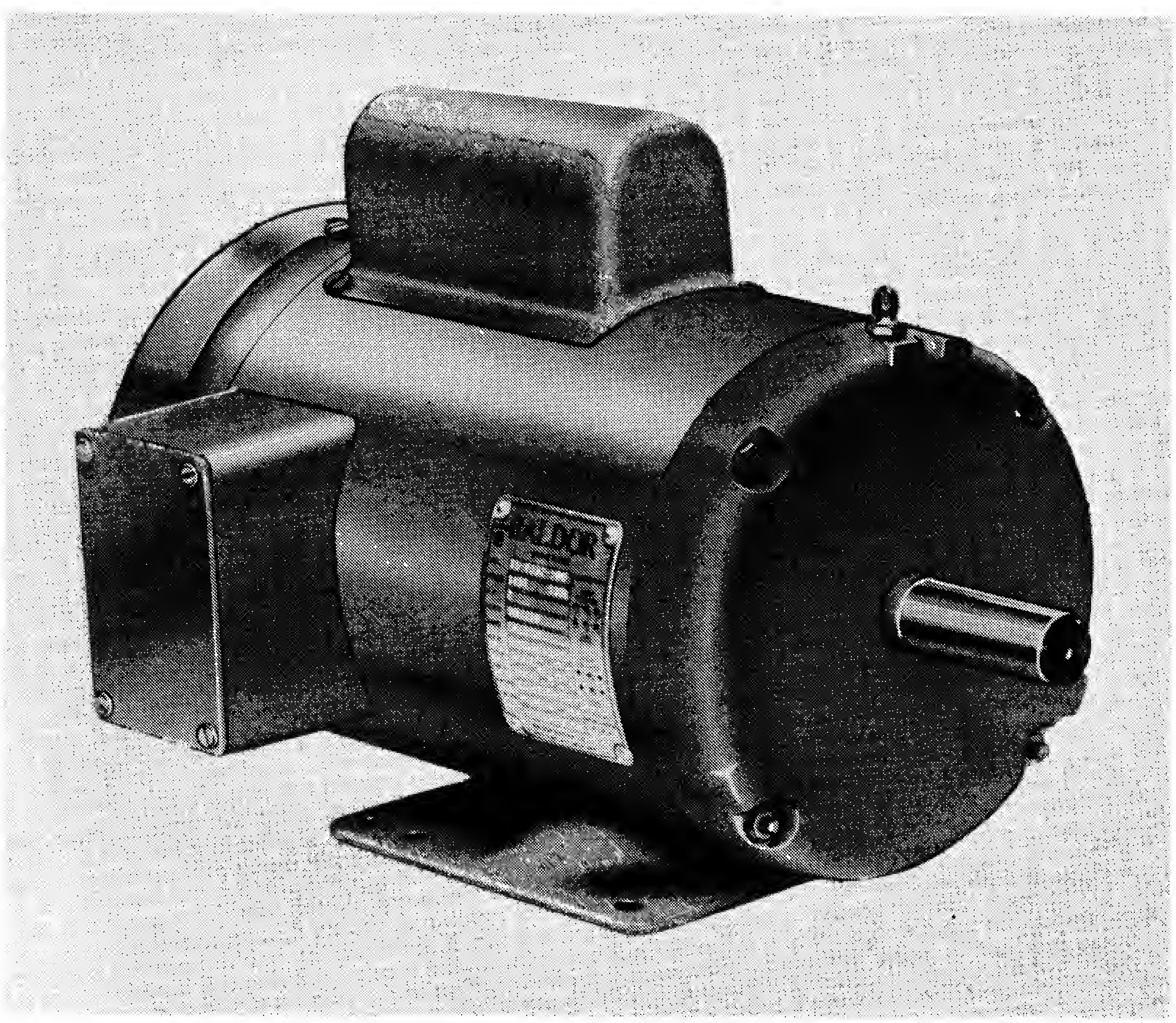


Fig. 1-1. Capacitor-start motor. *(Baldor Electric Co.)*

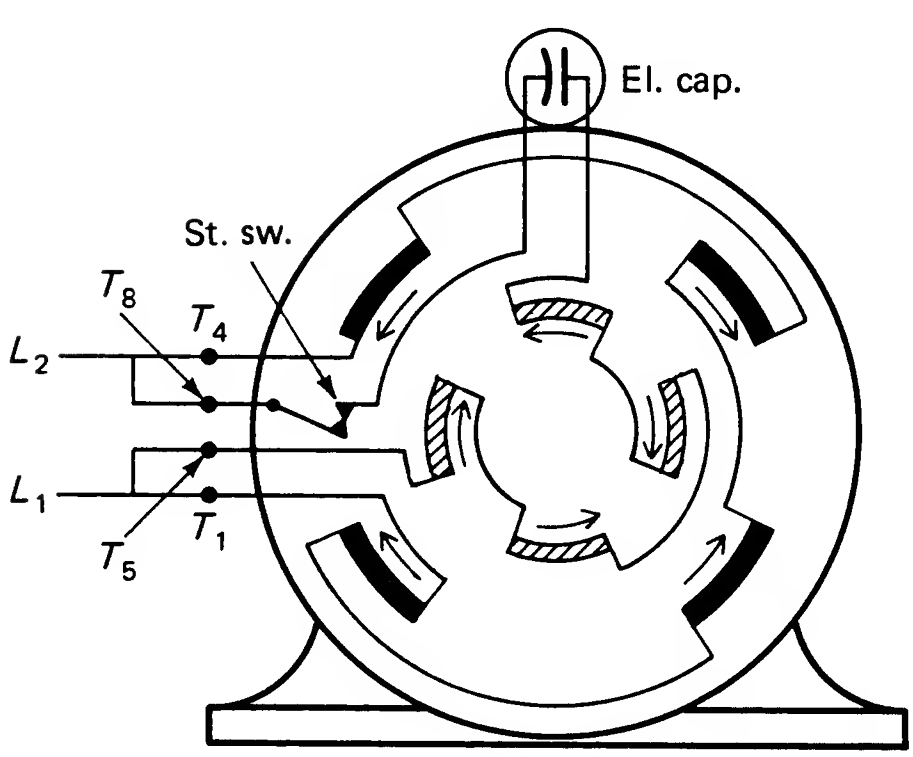


Fig. 1-2. Capacitor-start motor showing the approximate location of the windings and components.

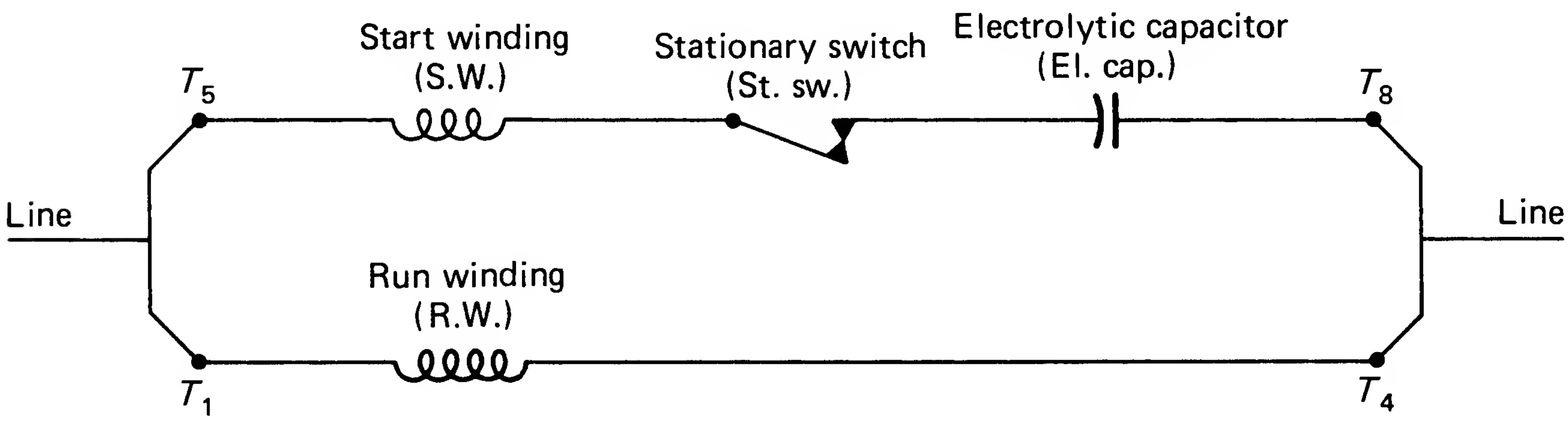


Fig. 1–3. Schematic diagram of the motor in Fig. 1-2. All numbered leads are accessible or come out of the motor.

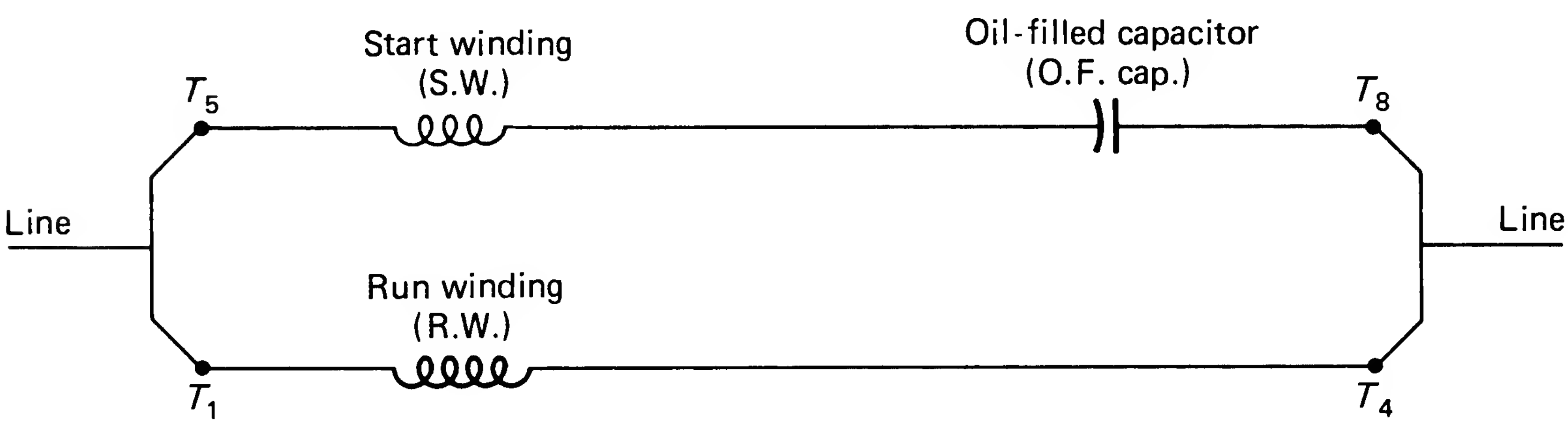


Fig. 1–4. Schematic of a permanent-split capacitor motor. All numbered leads are accessible or come out of the motor.

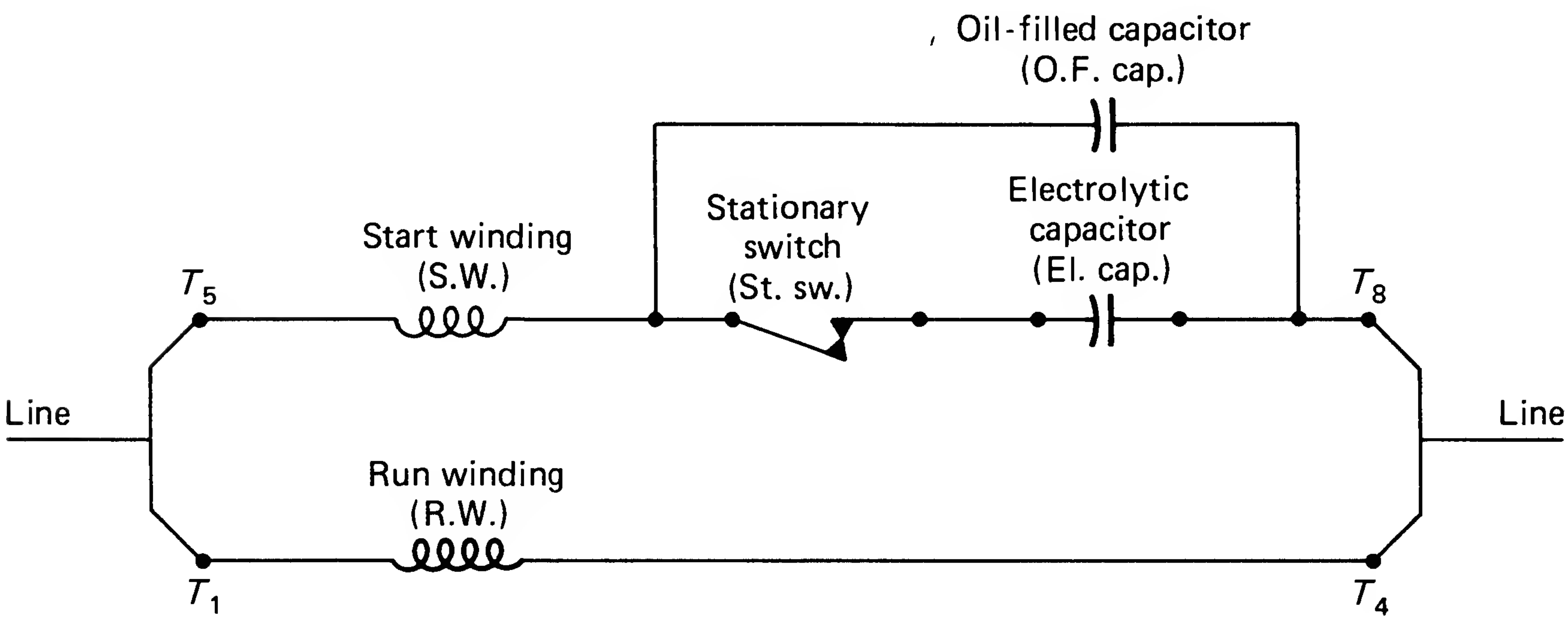


Fig. 1–5. Schematic of a two-value capacitor motor. All numbered leads are accessible or come out of the motor.

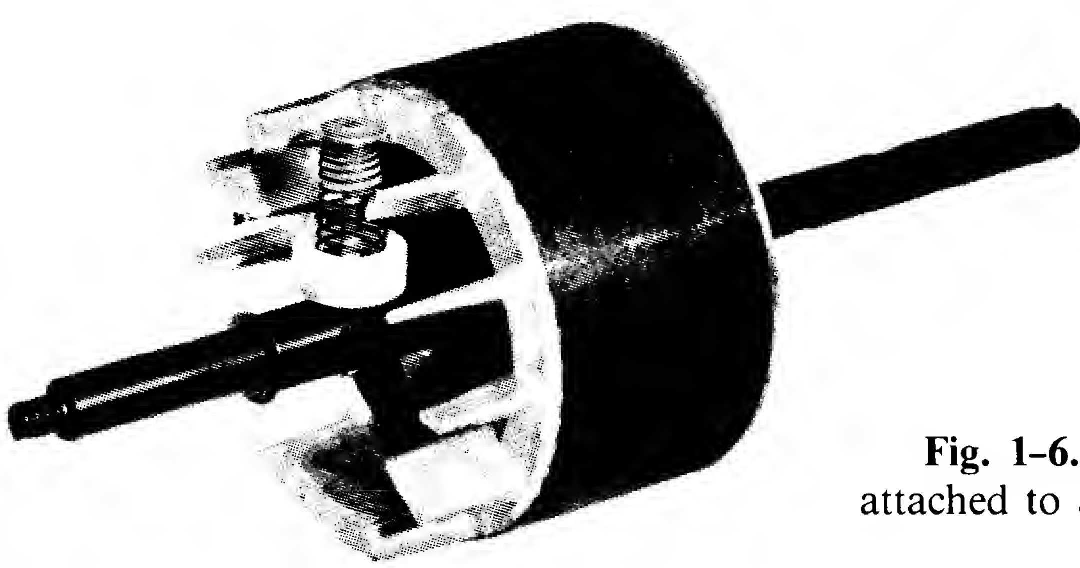


Fig. 1-6. One type of rotating device attached to a rotor. *(Delco Products)*

Fig. 1-7. Stator of a capacitor-start motor. *(Baldor Electric Co.)*

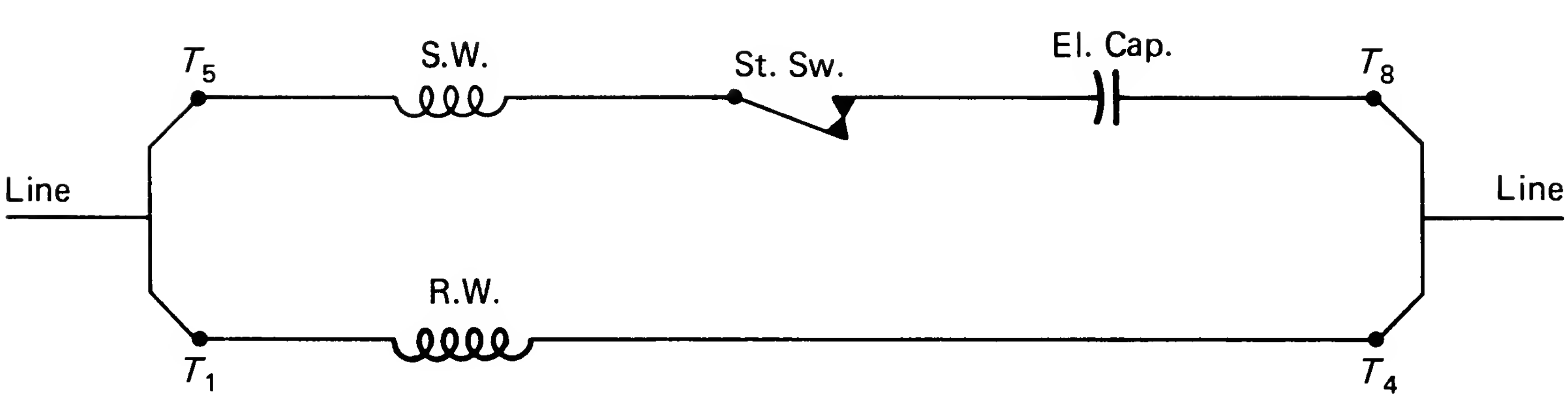
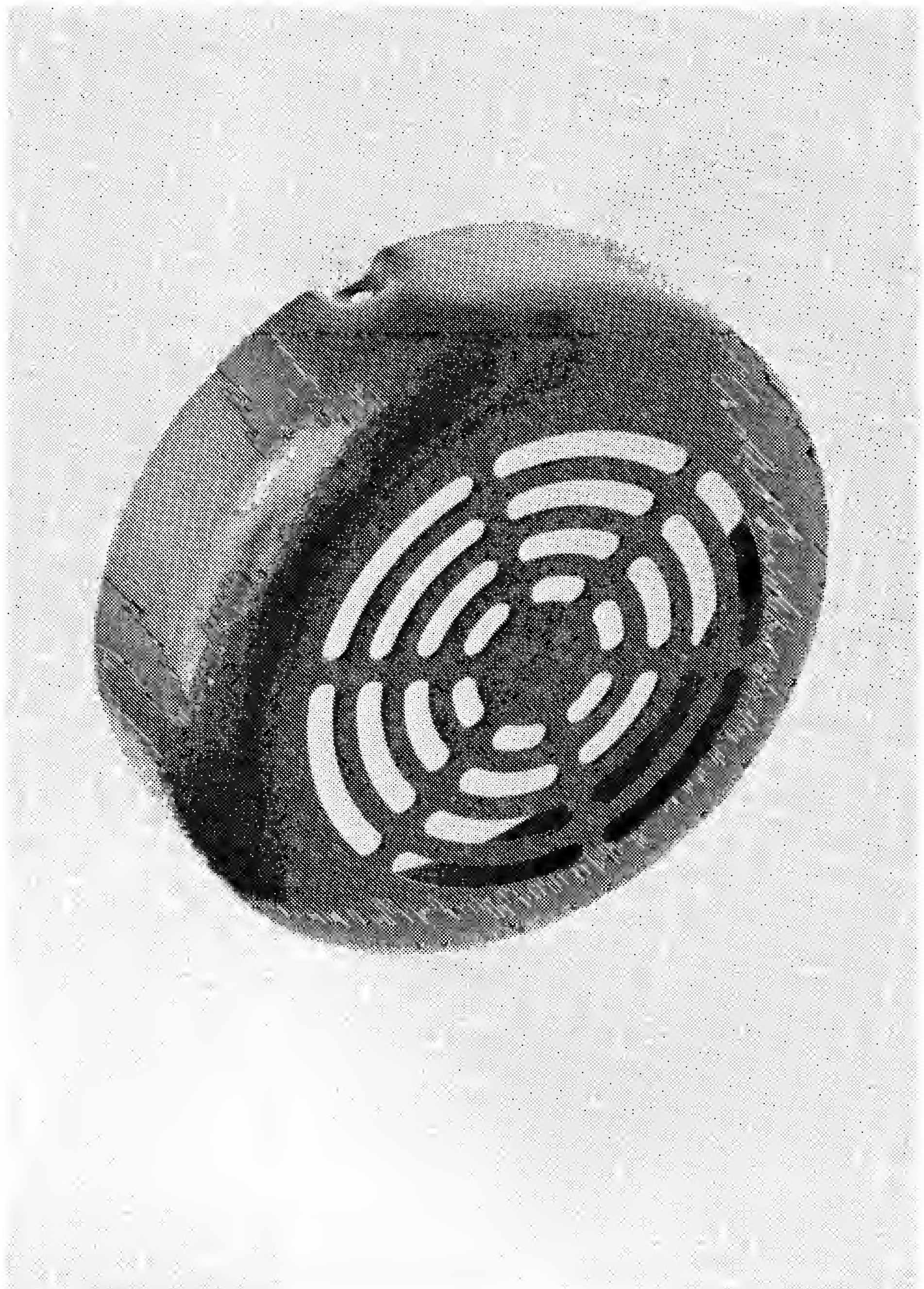


Fig. 1-8. Schematic of the stator in Fig. 1-7.



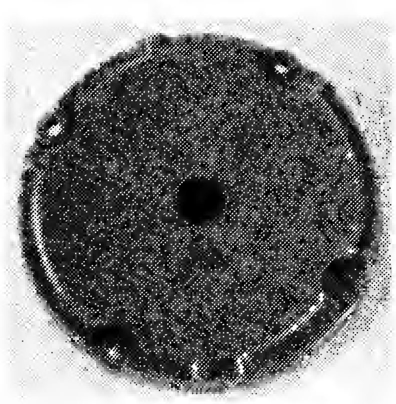


Fig. 1–9. One end plate of a single-phase motor. *(Baldor Electric Co.)*

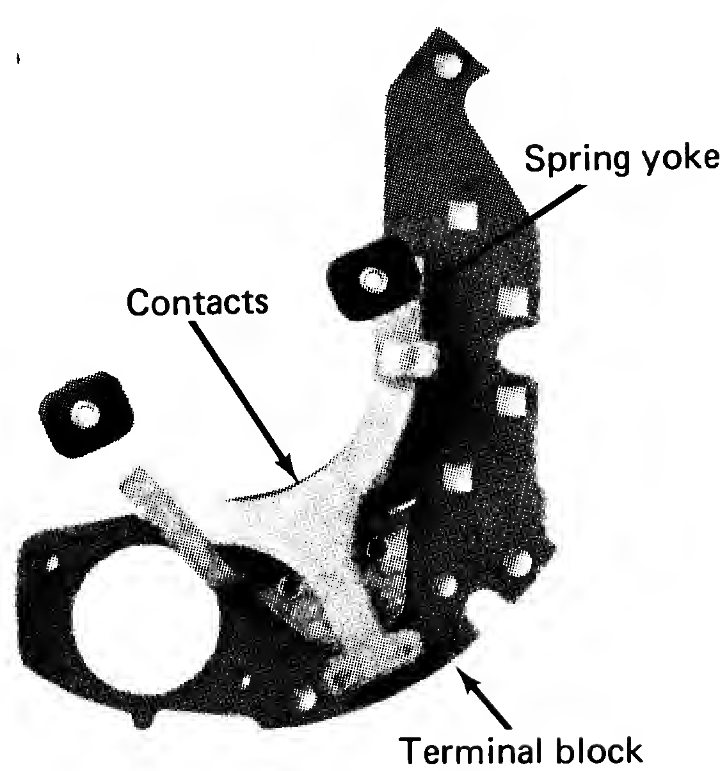


Fig. 1–10. Stationary switch of a single-phase motor. *(General Electric Co.)*

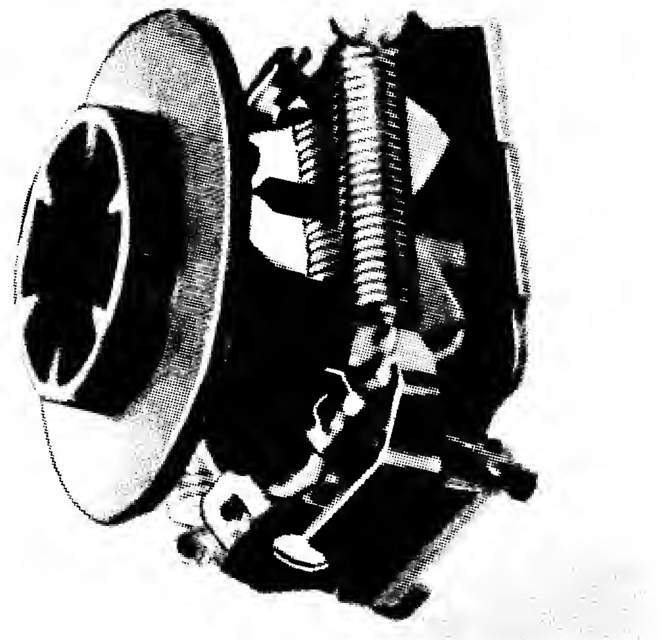


Fig. 1-11. Centrifugal device from a single-phase motor. *(General Electric Co.)*

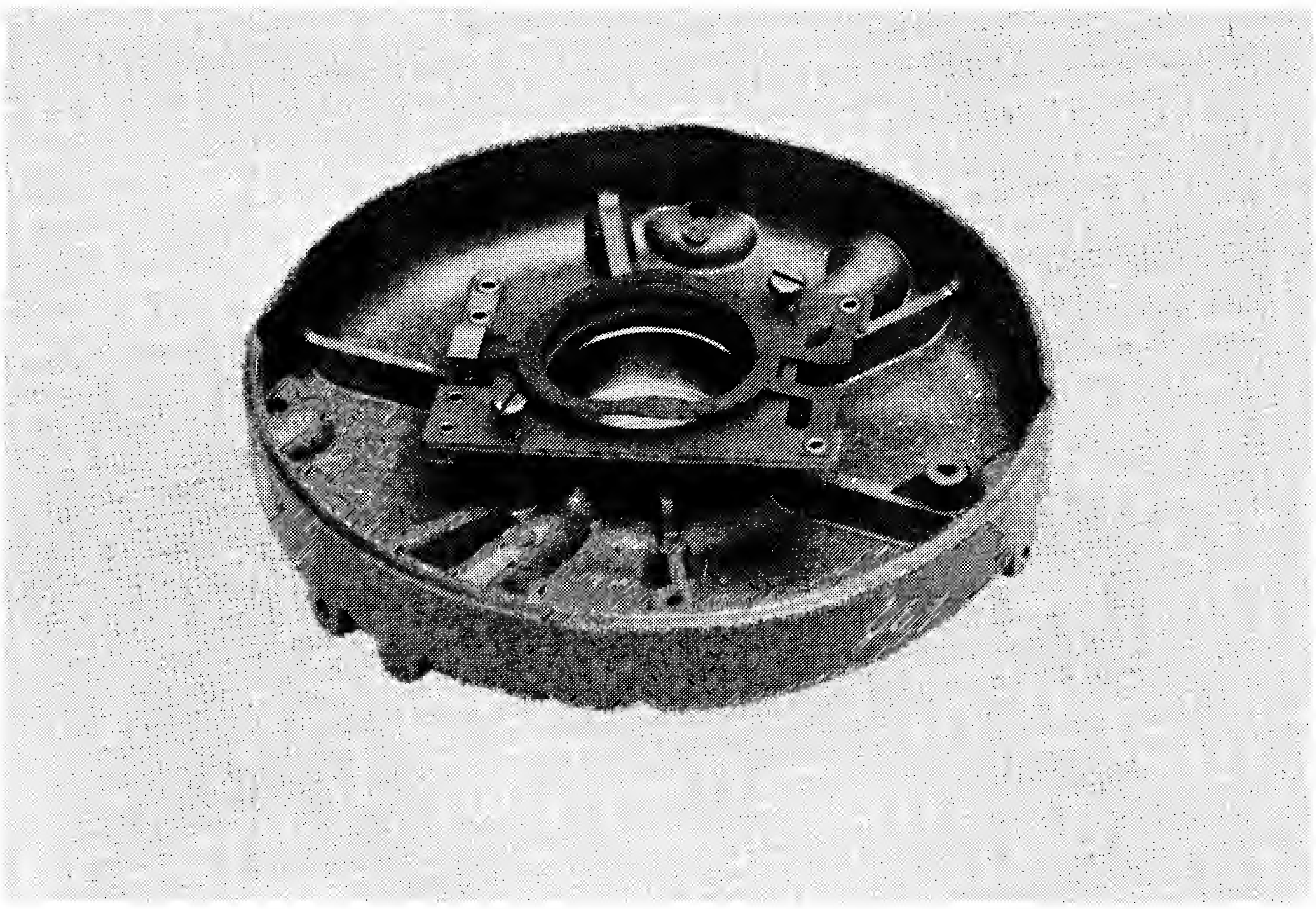


Fig. 1-12. Stationary switch mounted in an end plate. *(Baldor Electric Co.)*

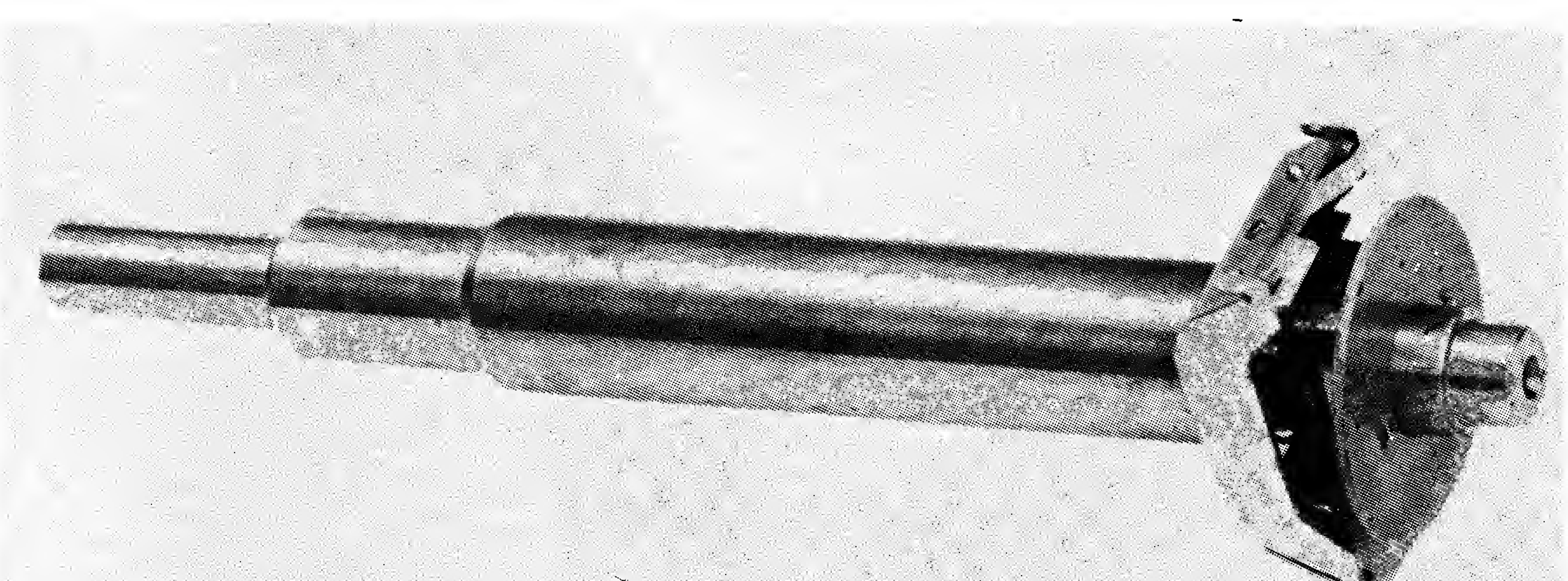
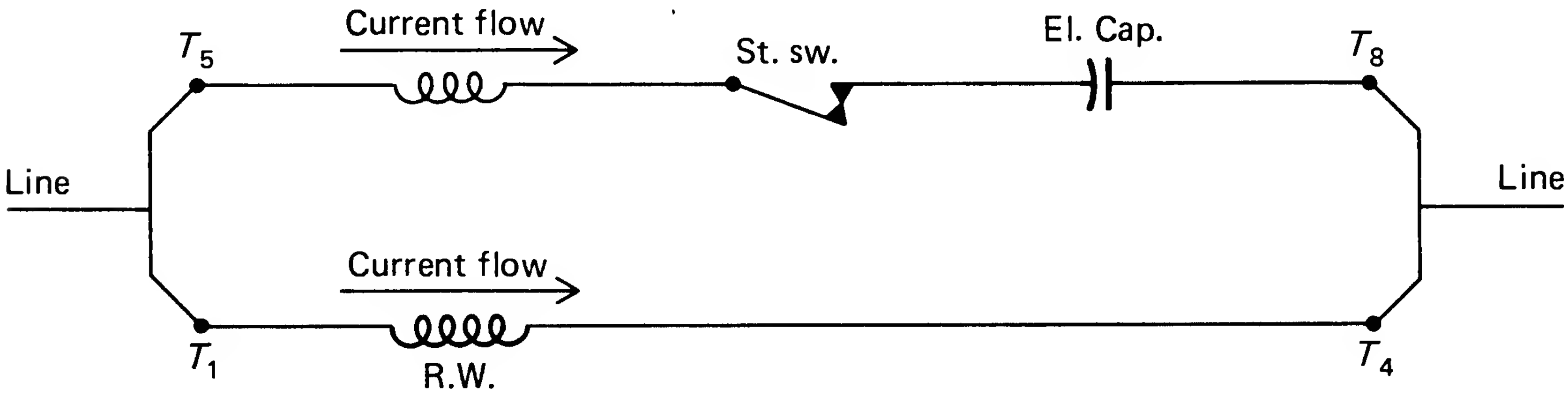
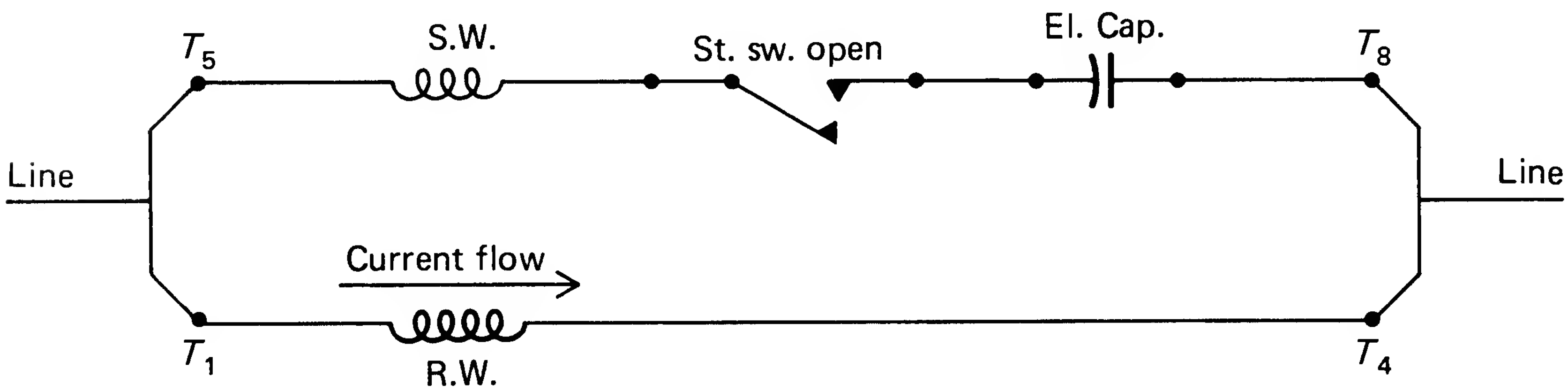


Fig. 1-13. Centrifugal device mounted on the rotor shaft. *(Baldor Electric Co.)*



a) Current flow when starting



b) Current flow when motor is at full speed

Fig. 1-14. Schematic of a capacitor-start motor when it is in the off position or during the start (a). When the motor is at full speed (b), the current flows only through the run winding. The stationary switch contacts open at 75 percent of full speed.

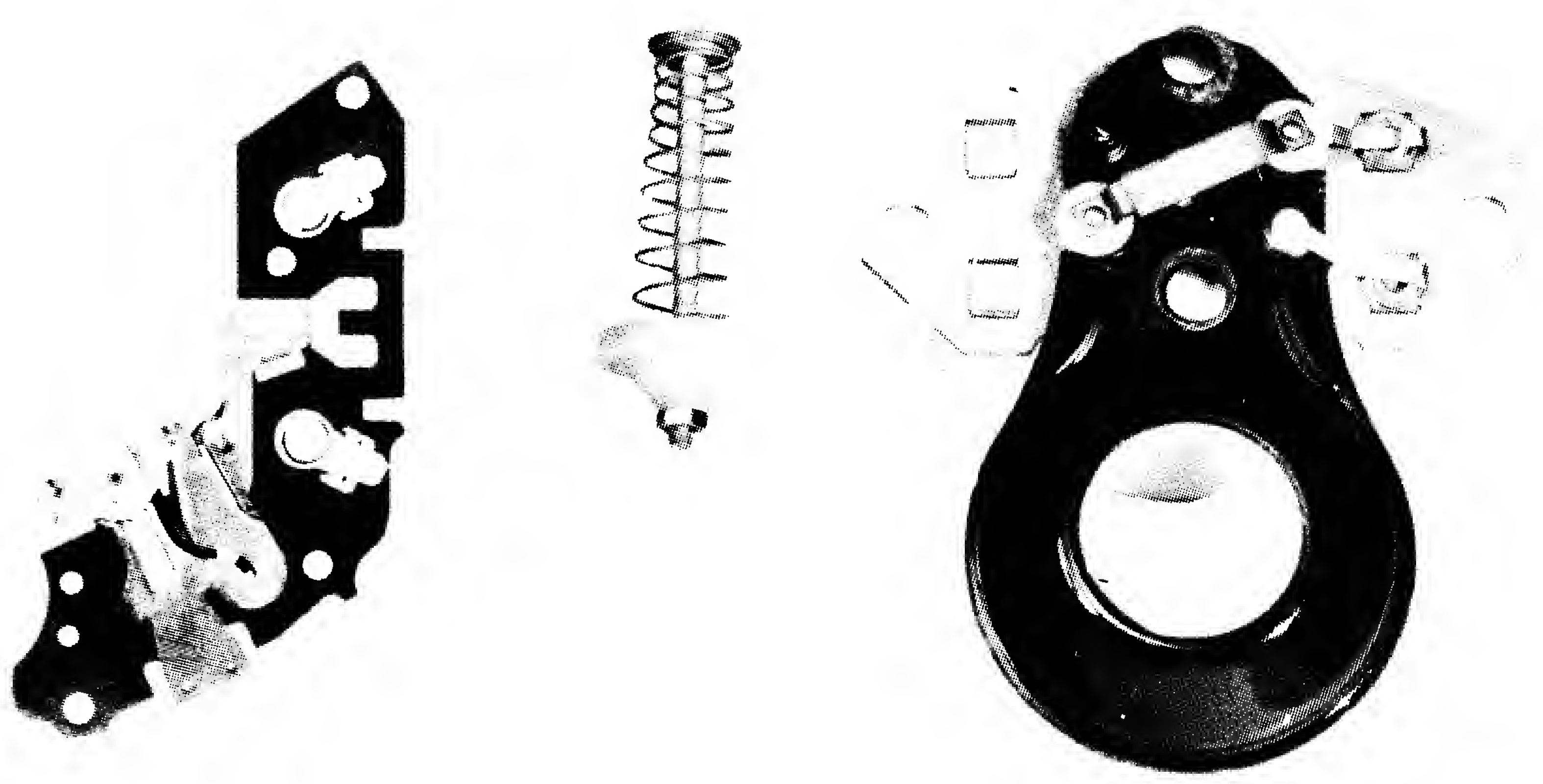


Fig. 1-15. Two variations of the stationary switch. *(Delco Products* and *General Electric Co.)*

Fig. 1-16. Electrolytic capacitor. *(Sprague Electric)*

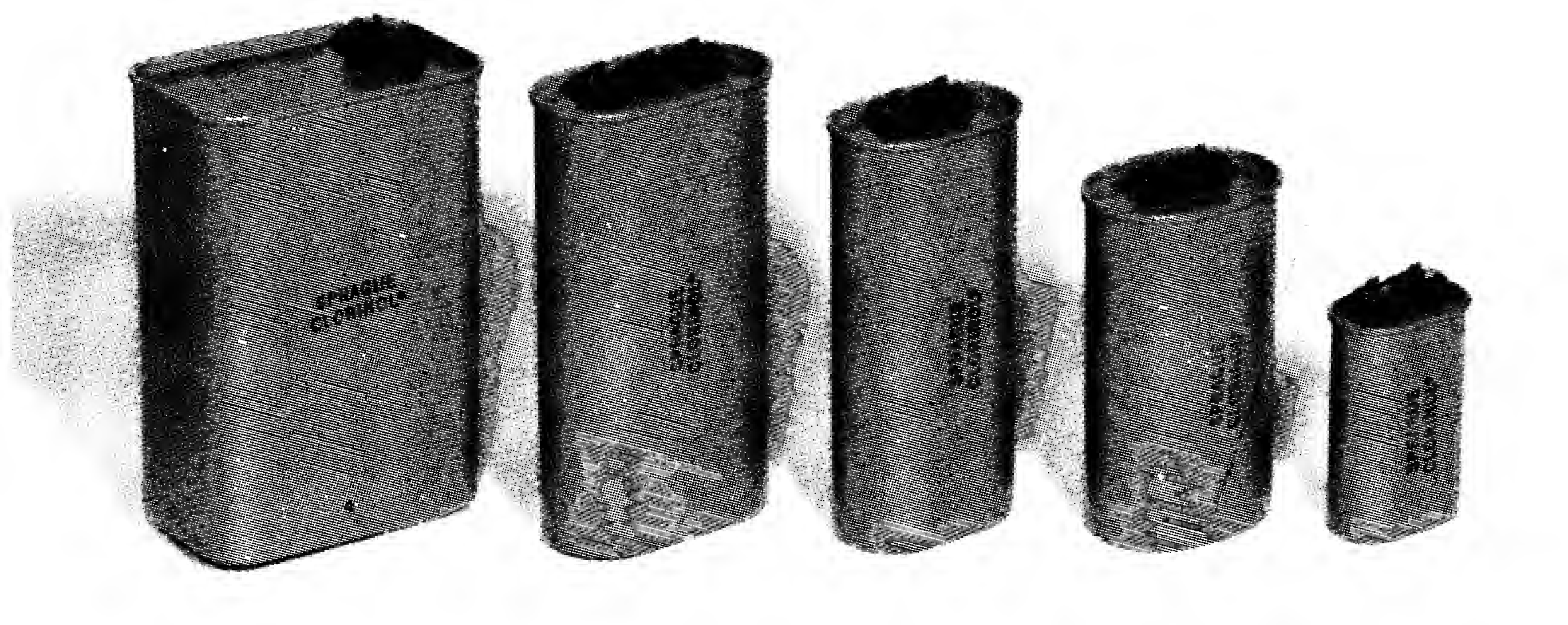


Fig. 1-17. Oil capacitors. *(Sprague Electric)*

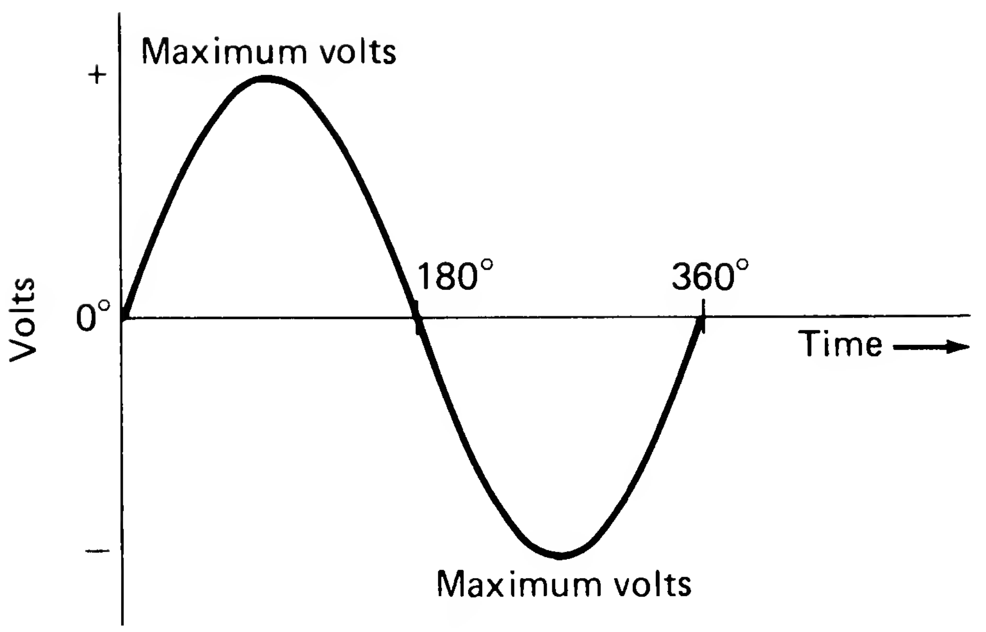


Fig. 1-18a. The shape of the sine wave as seen on an oscilloscope.

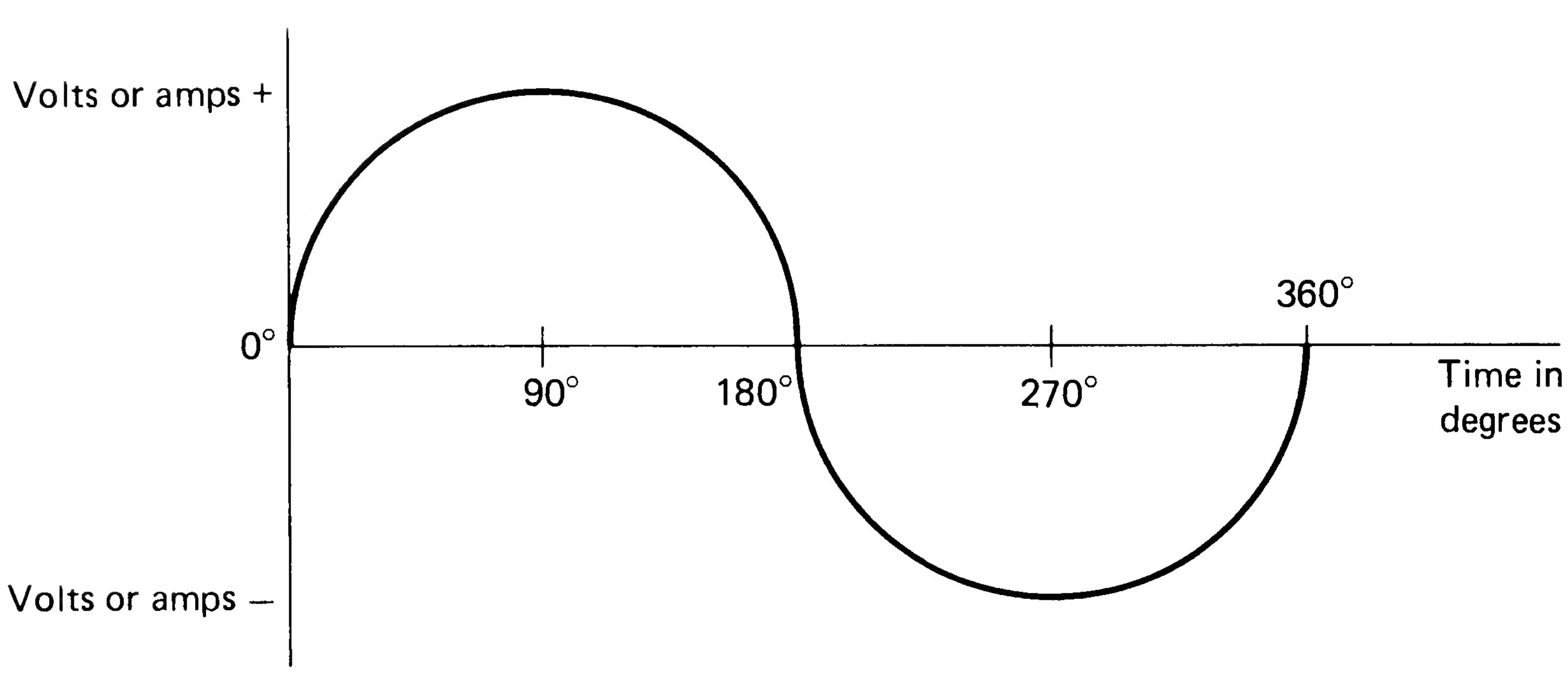


Fig. 1-18b. The single-phase sine wave as it will be drawn for illustrative purposes in this book.

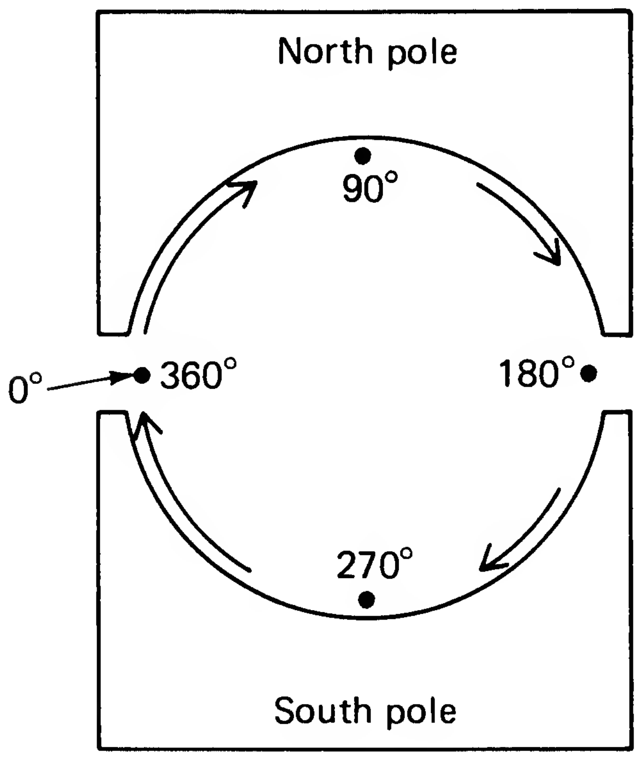


Fig. 1–19. The two-pole winding illustrating how electrical degrees compare with mechanical degrees.

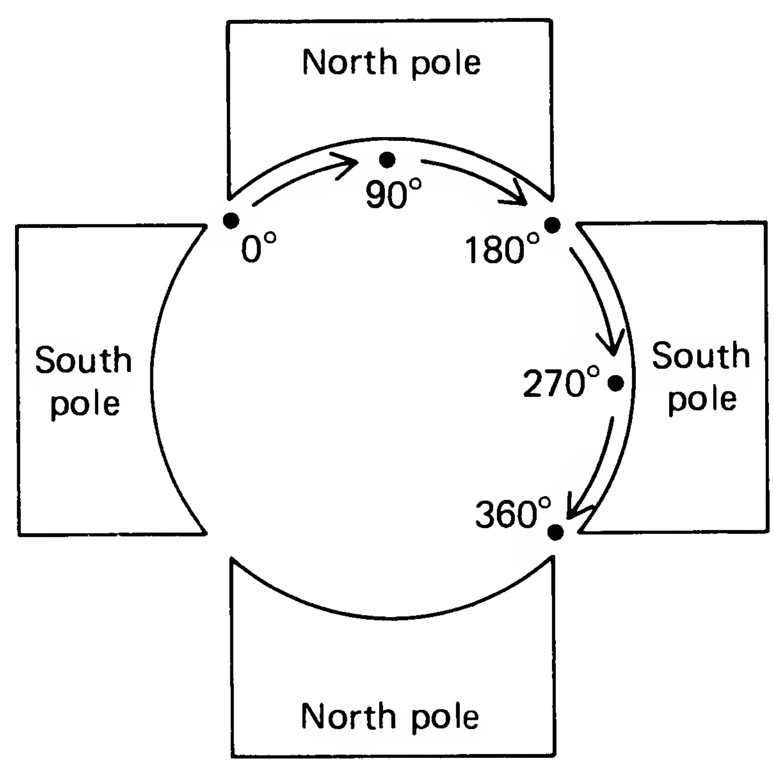


Fig. 1–20. A four-pole winding illustrating how 360 electrical degrees compare with 360 mechanical degrees.

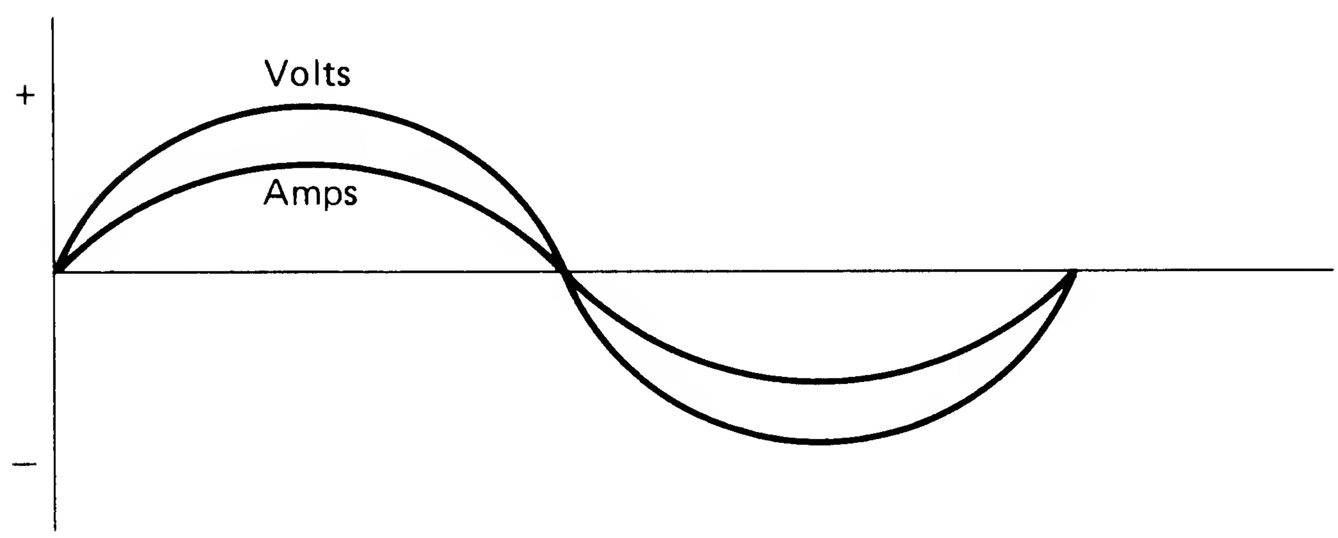


Fig. 1–21. The single-phase sine wave with both volts and amperes.

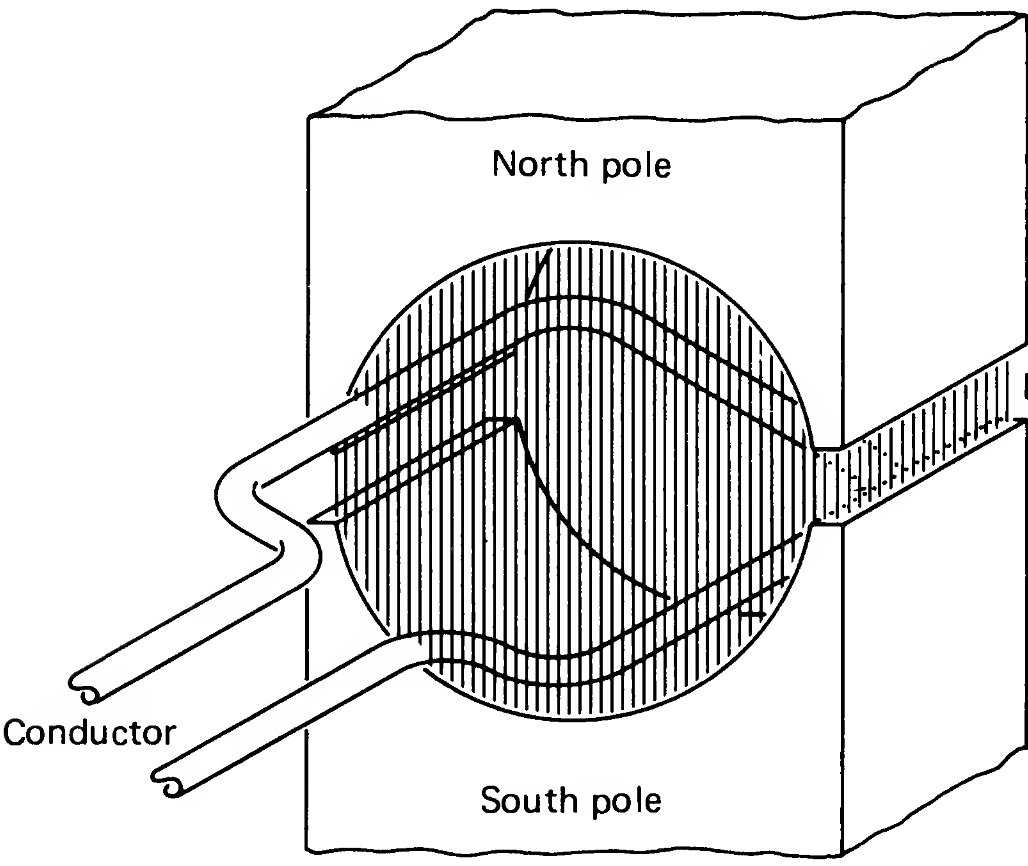


Fig. 1-22. A generating conductor of an alternating current generator or alternator cutting the lines of force of a magnetic field.

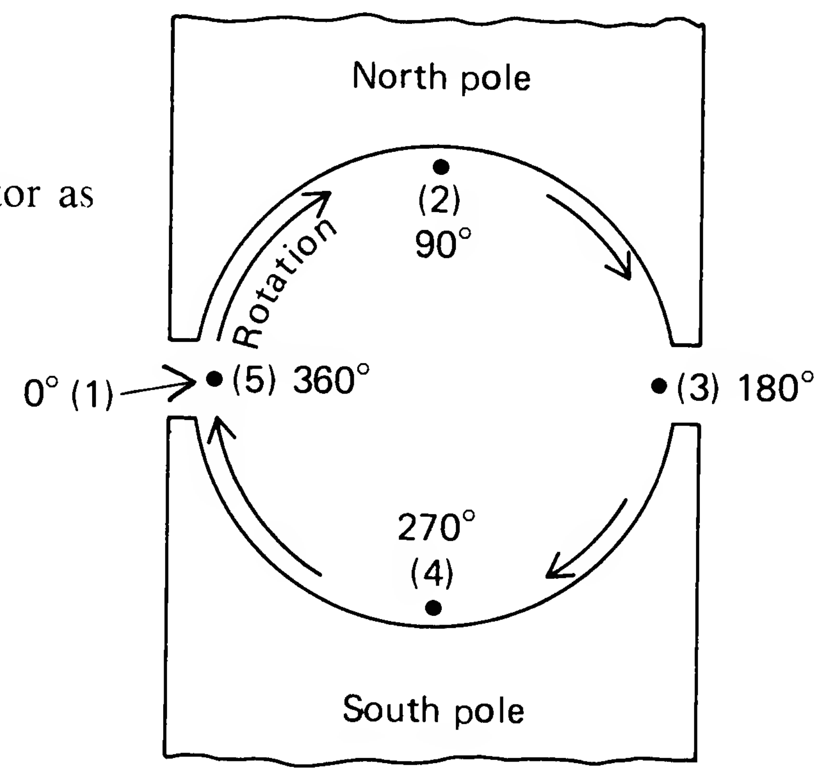


Fig. 1-23. Positions of a conductor as voltage is generated.

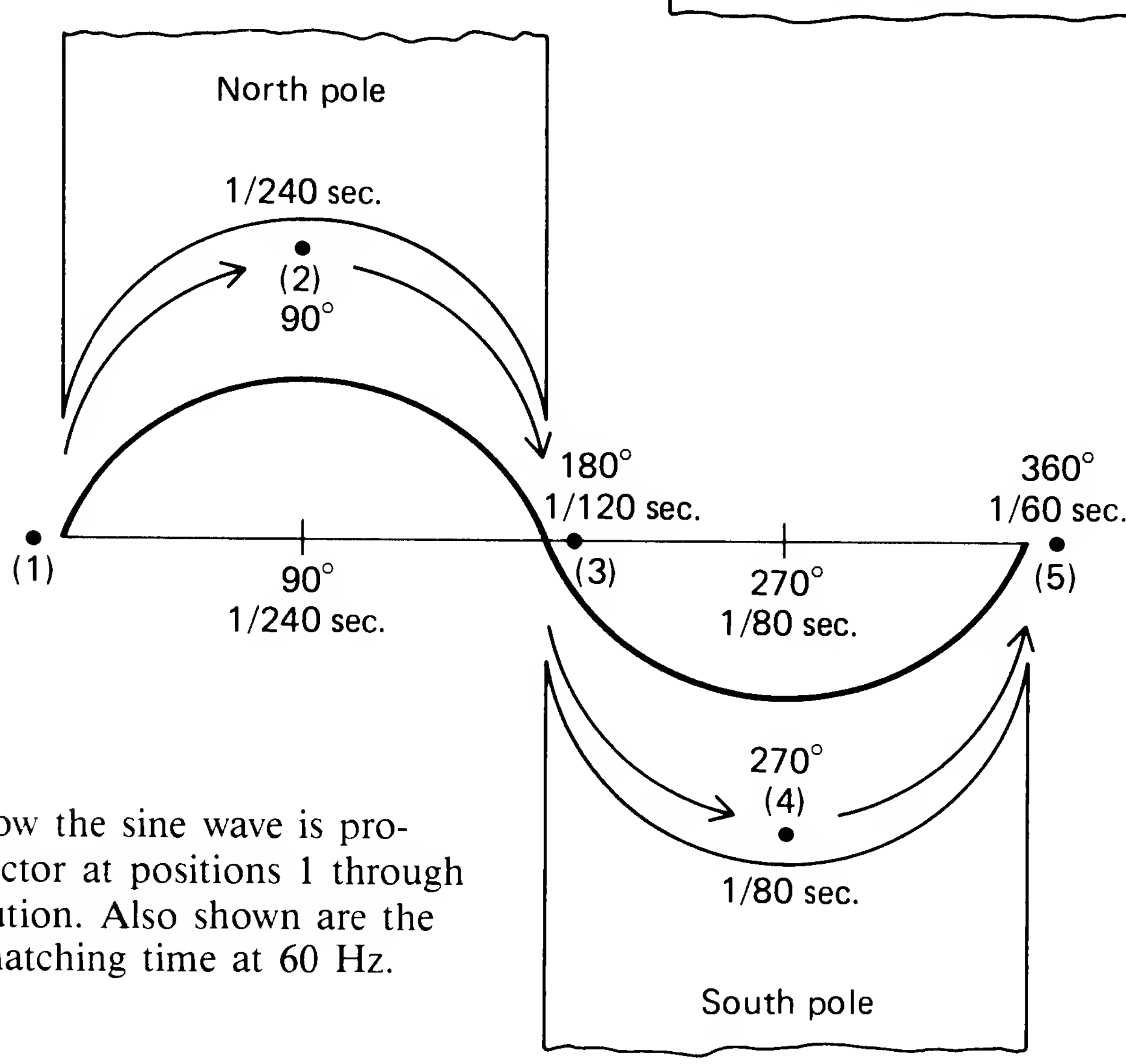
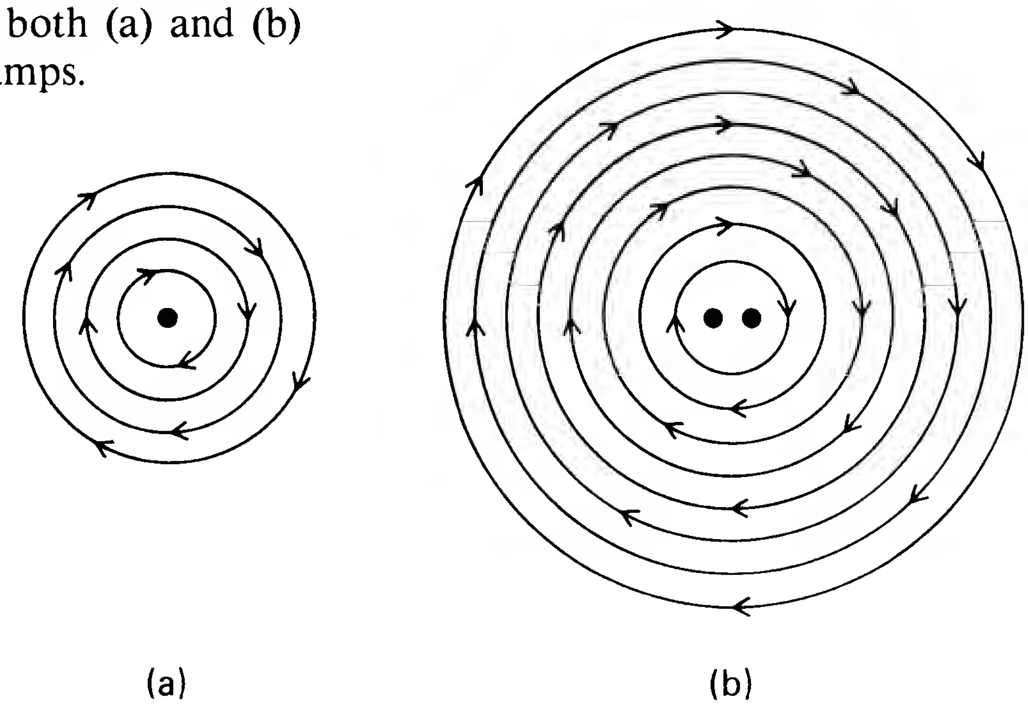


Fig. 1-24. How the sine wave is produced. The conductor at positions 1 through 5 make one revolution. Also shown are the degrees and the matching time at 60 Hz.

Fig. 1-25. The magnetic field around one conductor (a) and the combined magnetic fields of two conductors (b). The conductors of both (a) and (b) are carrying the same amount of amps.



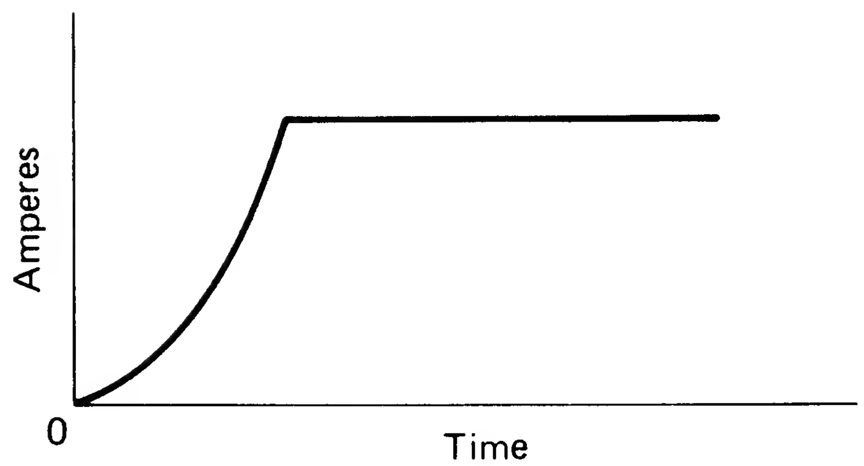
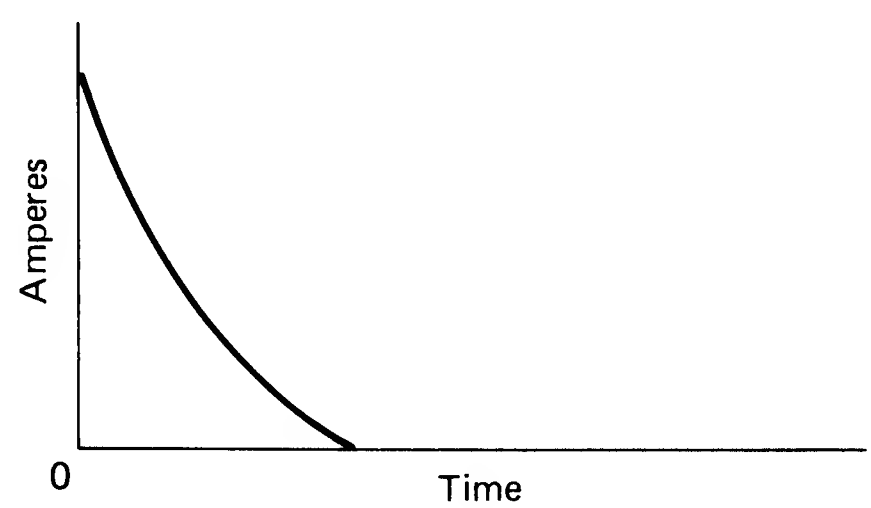


Fig. 1-26. The delay in current flow because of inductive reactance in a coil of wire.

Fig. 1-27. Current flow maintained briefly because of inductive reactance in the same coil of wire when the voltage is shut off. The length of time that the current is delayed matches exactly the length of time that the current is maintained.



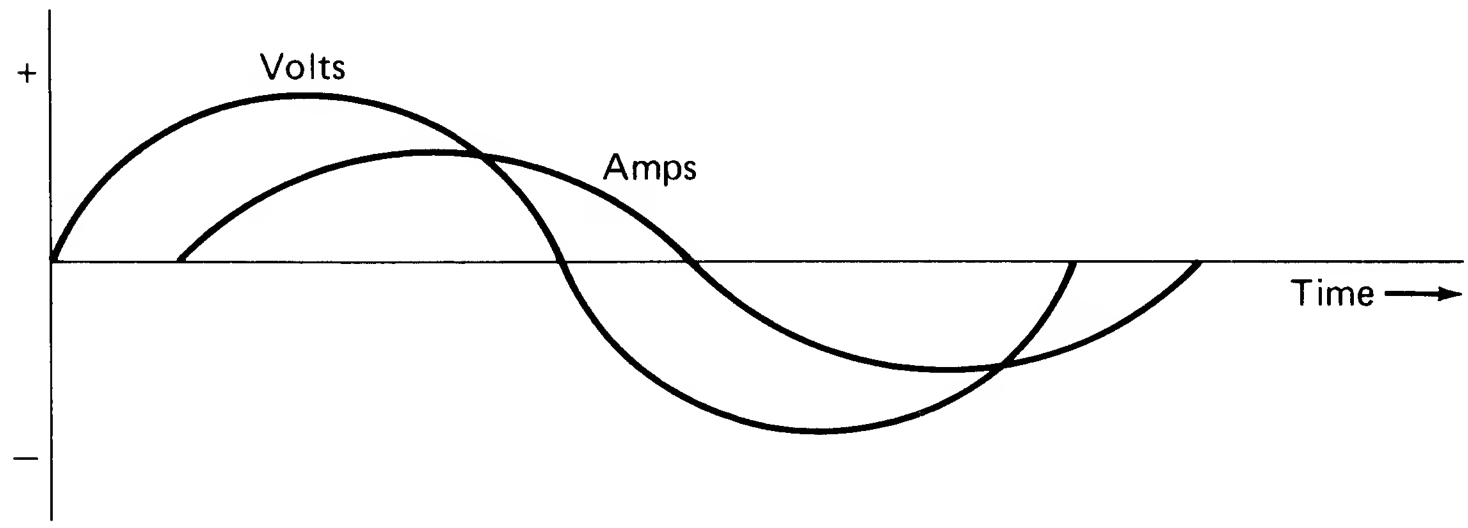


Fig. 1-28. The delay in current flow in an ac circuit caused by inductive reactance in a coil of wire.

Figures 1-25; 1-26; 1-27; 1-28

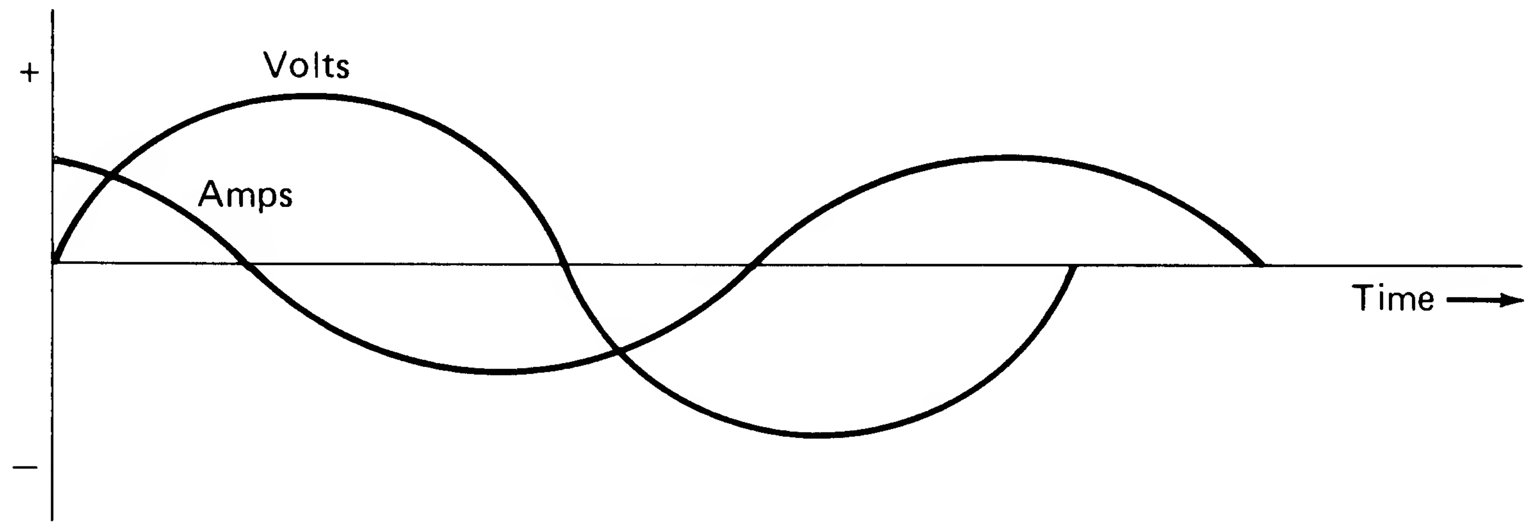


Fig. 1-29. The leading current flow in an ac circuit caused by capacitive reactance.

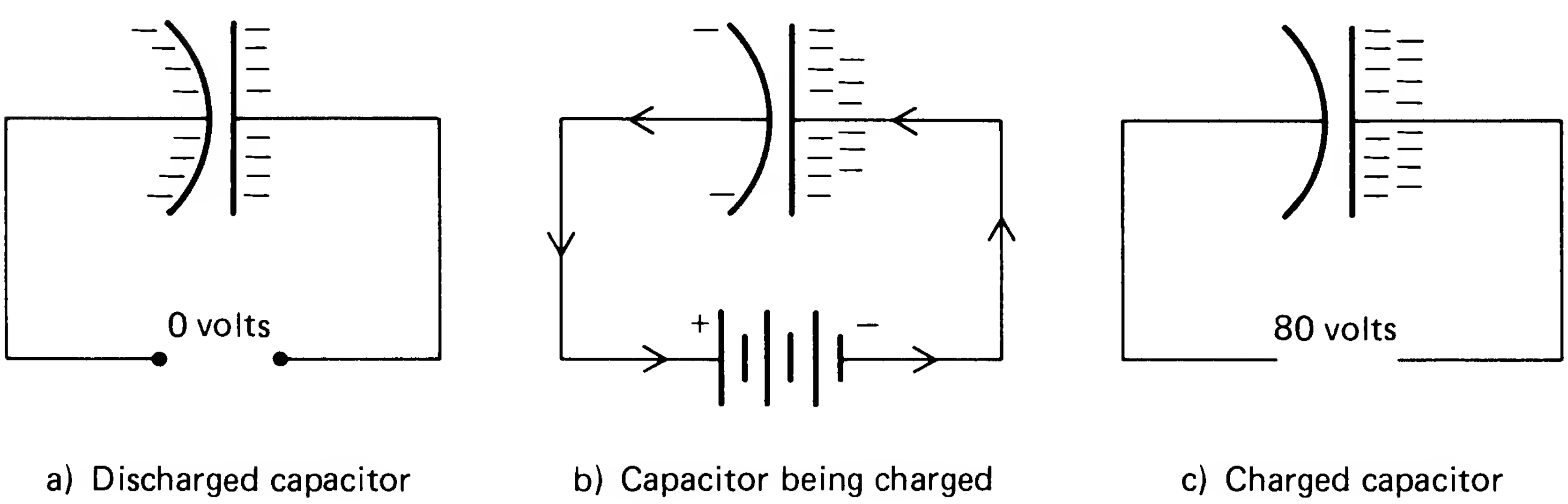


Fig. 1-30. Charging a capacitor.

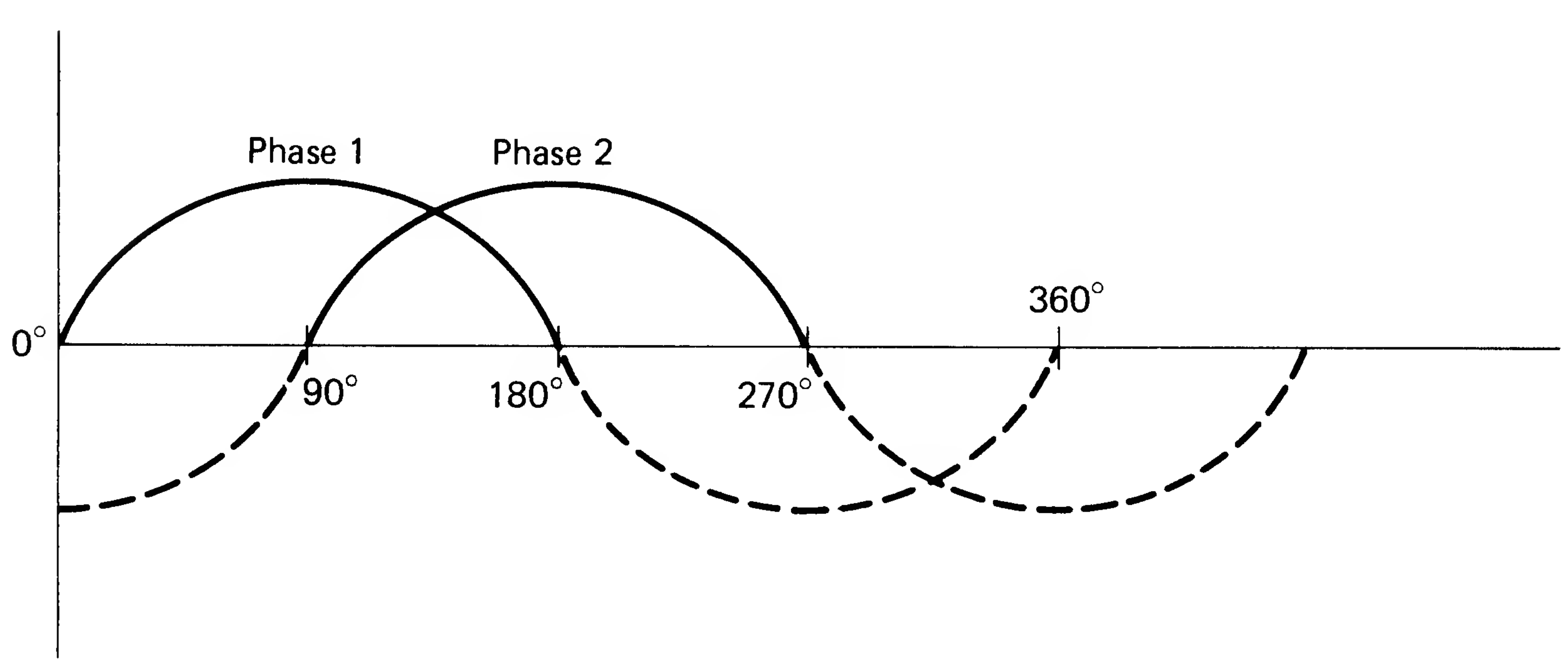


Fig. 1-31. Two-phase sine wave.

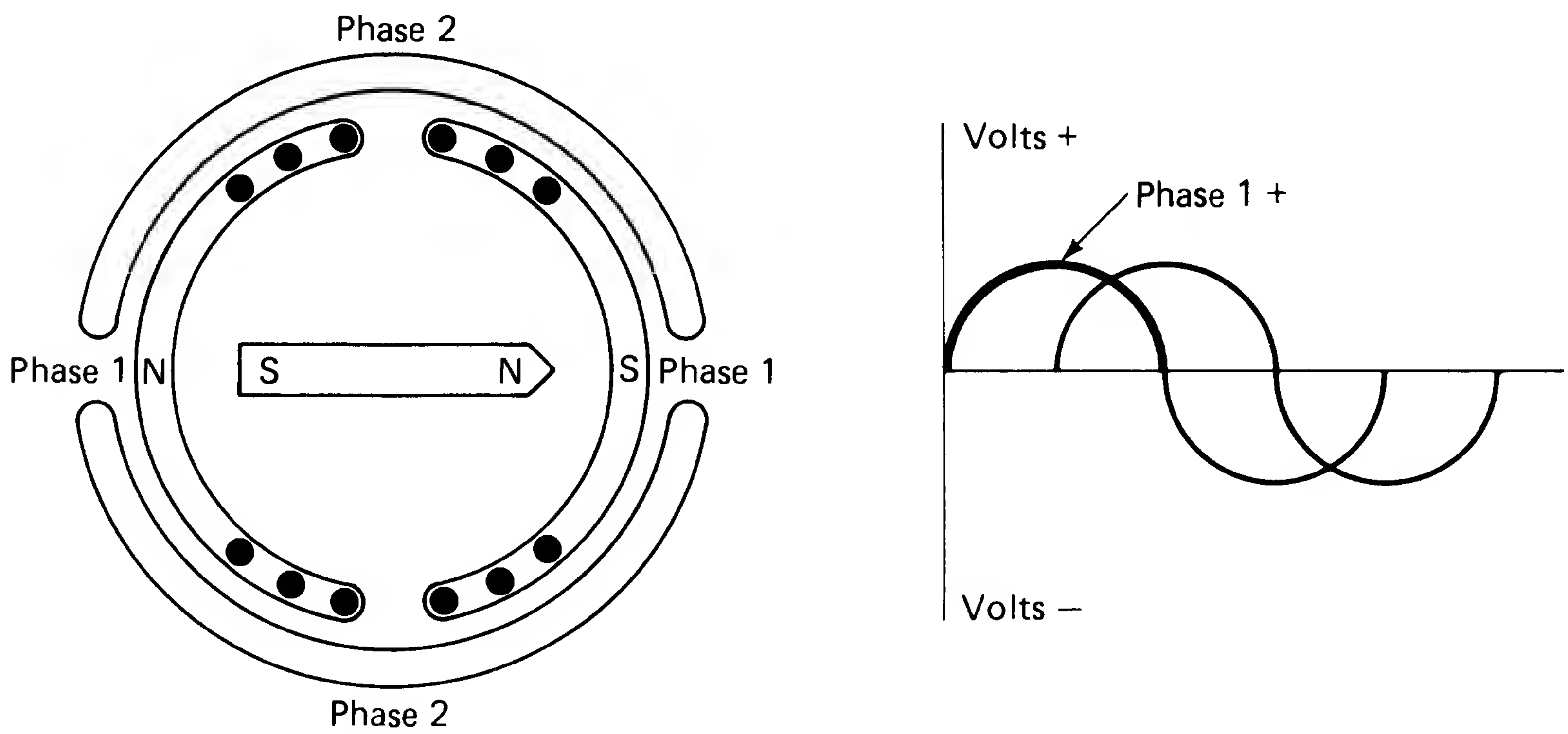


Fig. 1–32a. Two-phase stator with phase 1 energized and corresponding position on sine wave.

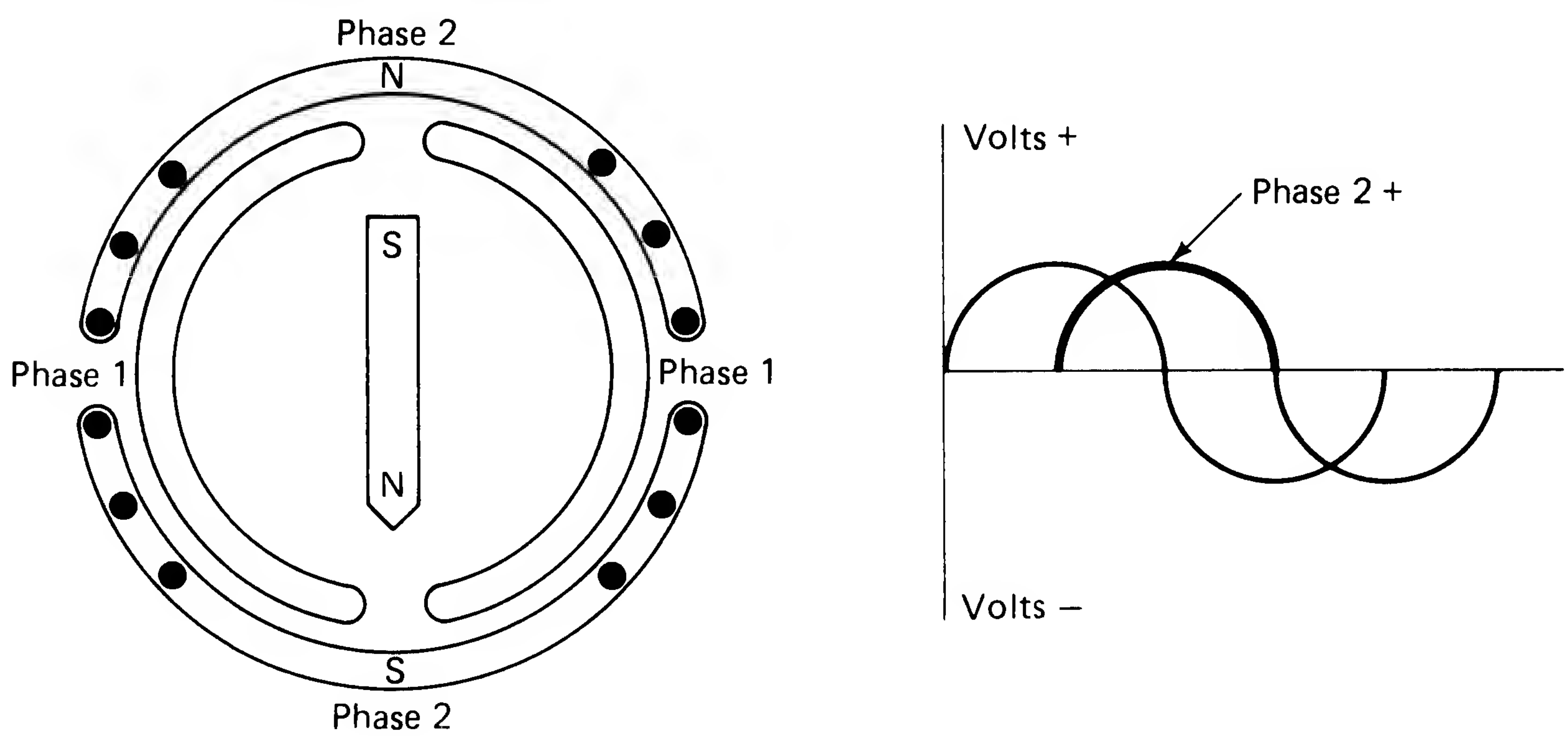


Fig. 1–32b. Phase 2 energized and corresponding position on sine wave 1/240 of a second later.

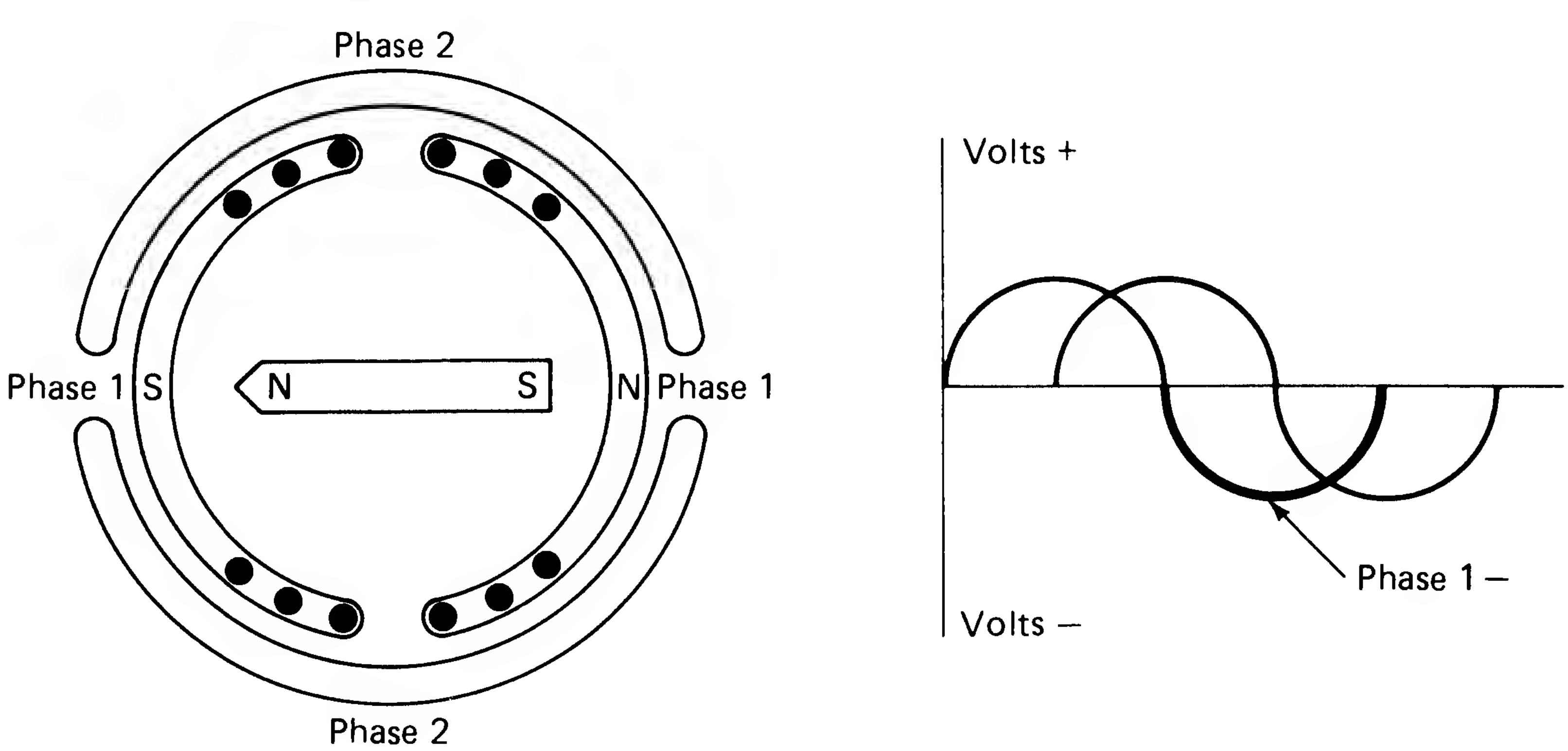


Fig. 1–32c. Phase 1 energized in opposite polarity, 1/240 of a second later, as shown on the sine wave.

Figures 1–32a; 1–32b; 1–32c

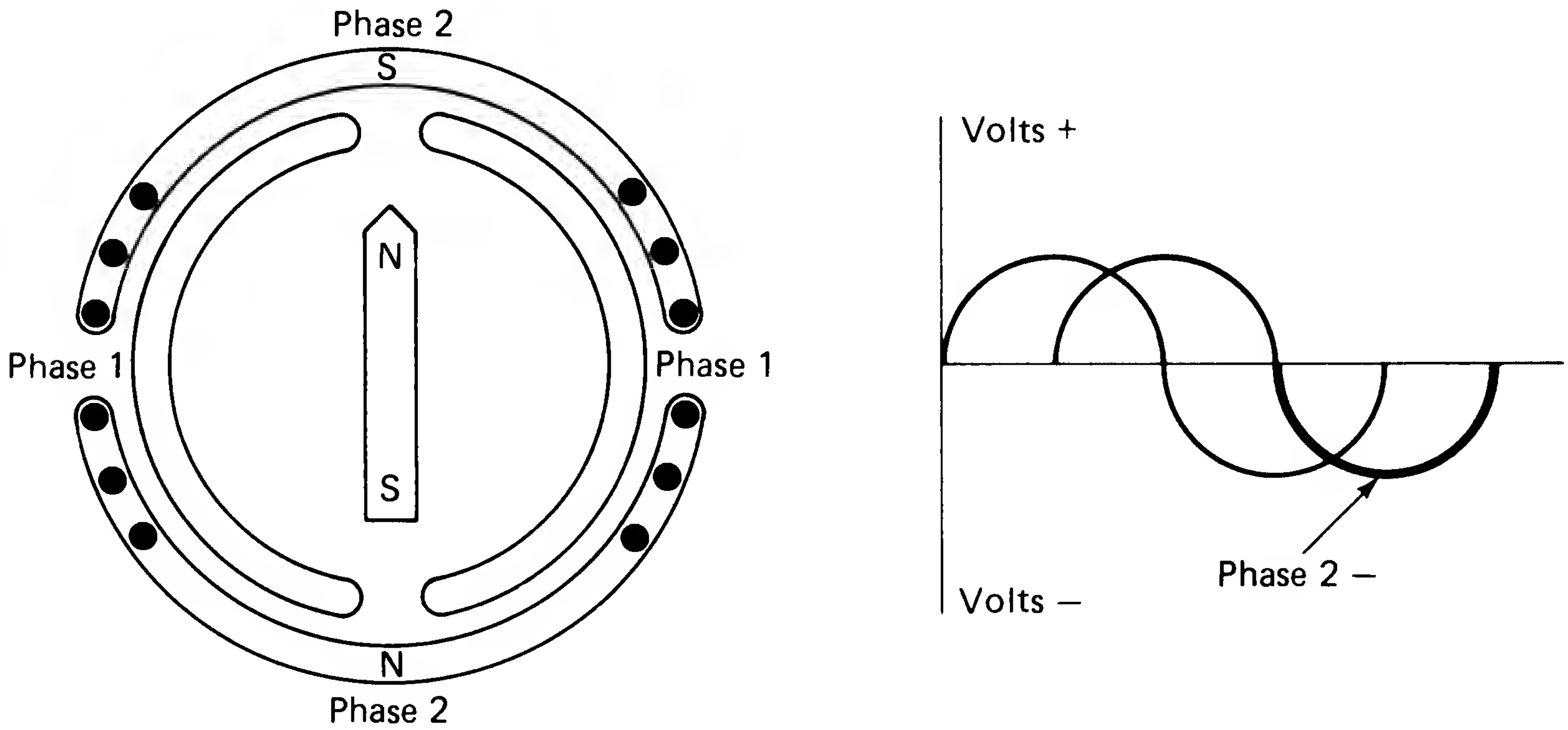


Fig. 1–32d. Phase 2 energized, as shown on sine wave 1/240 of a second later.

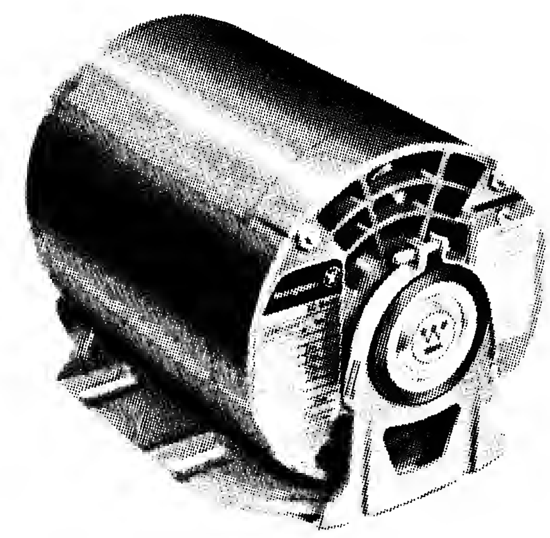


Fig. 1–33. A split-phase motor. *(Westinghouse Electric Co.)*

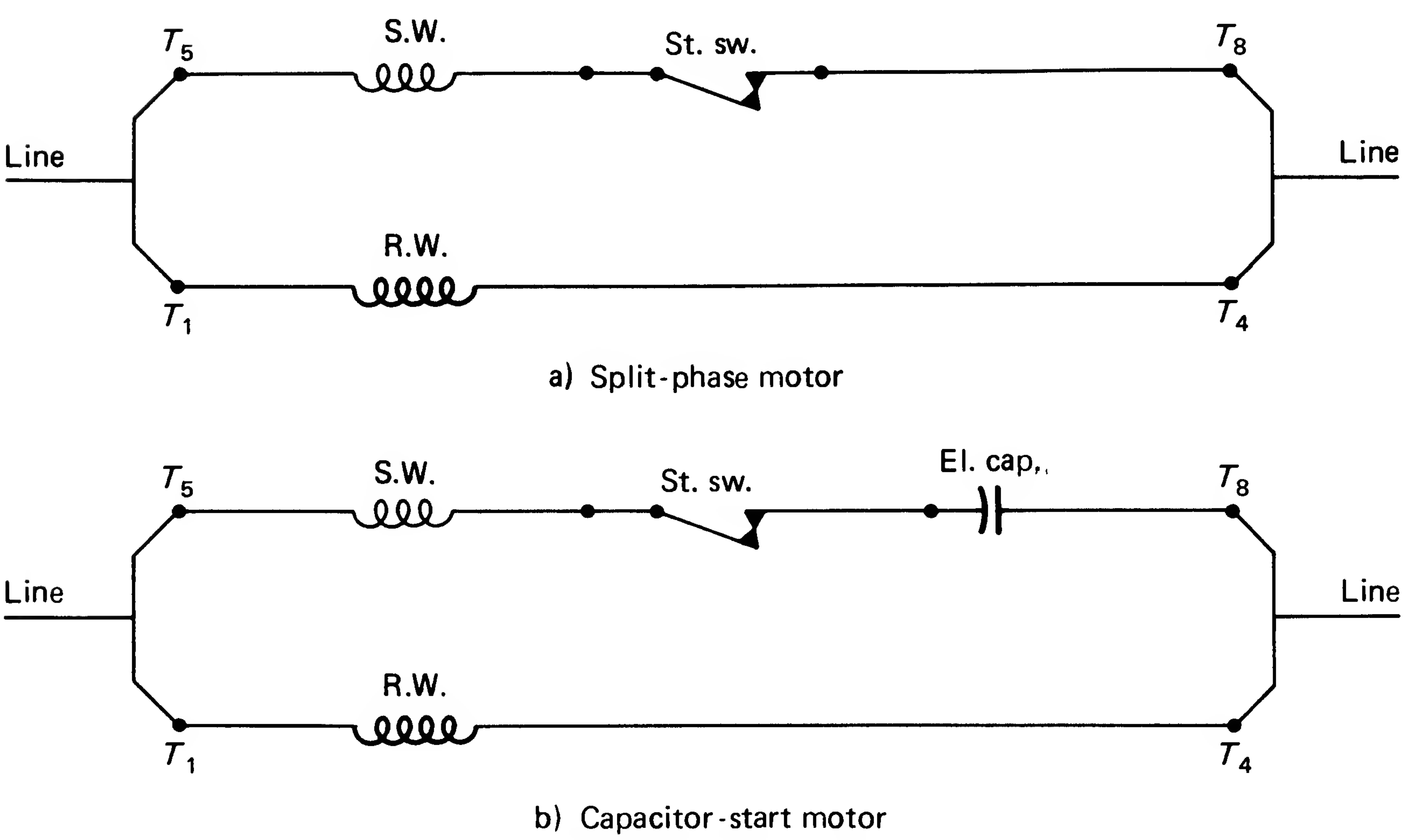


Fig. 1–34. Schematic of (a) a split-phase motor and (b) a capacitor-start motor.

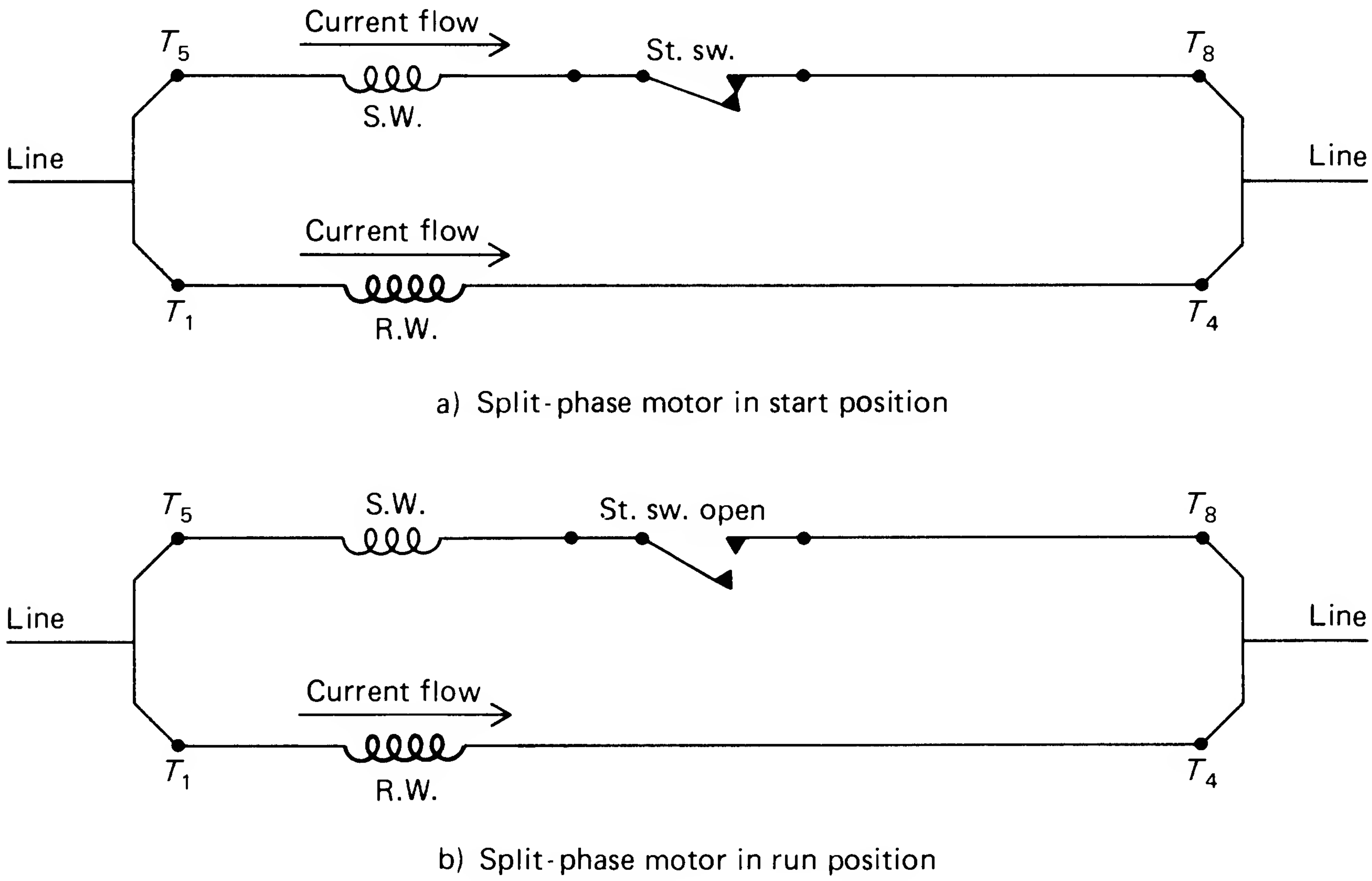


Fig. 1-35. Schematic of a split-phase motor in (a) start and (b) run positions.

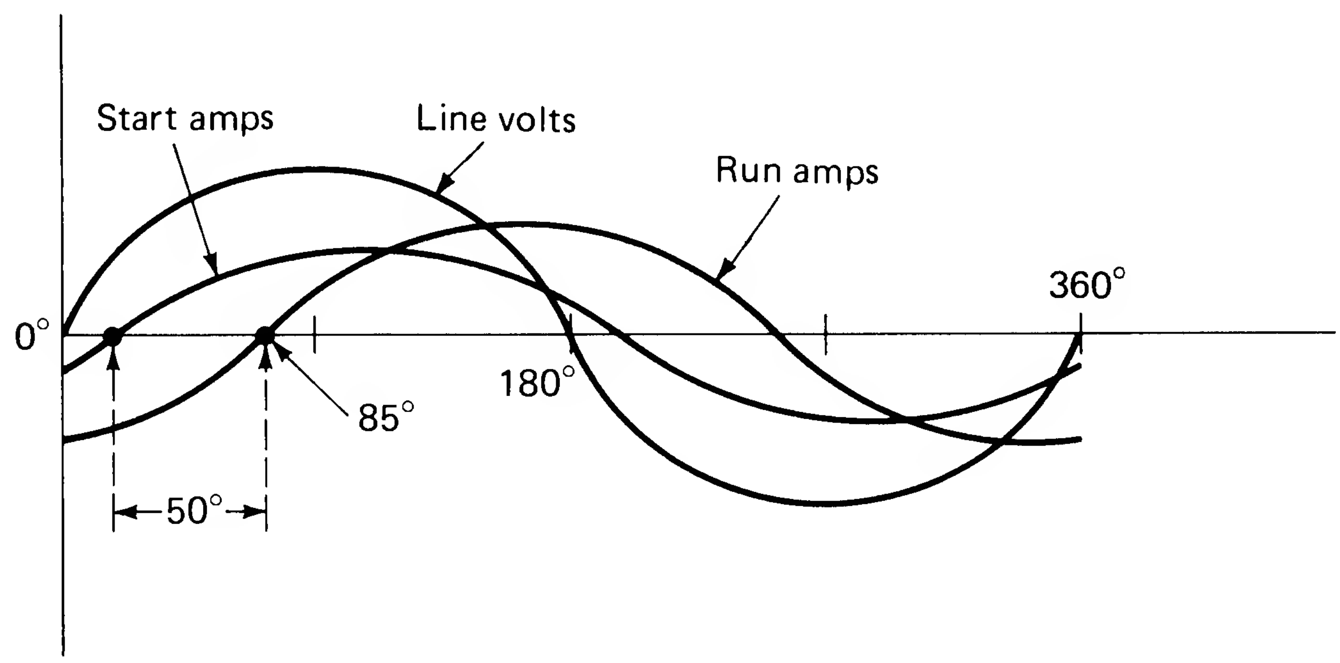


Fig. 1-36. Split-phase start-winding and run-winding amps 50° apart.

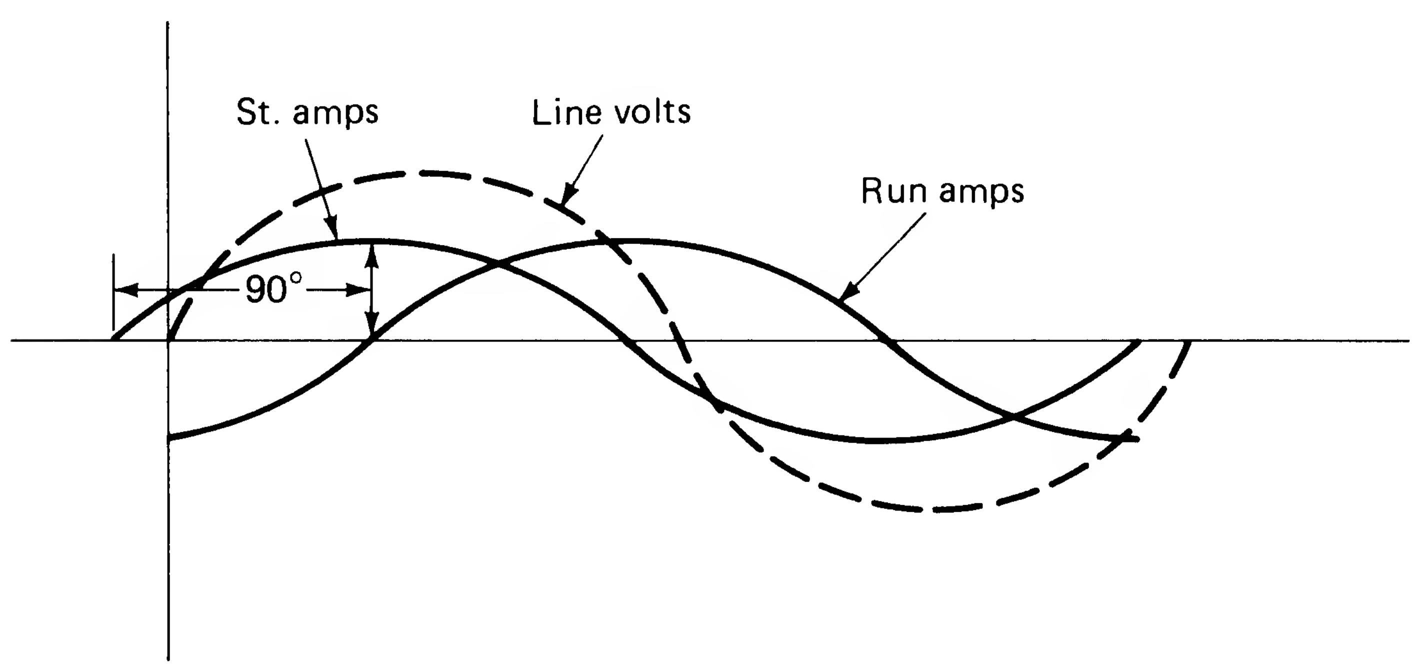


Fig. 1-37. Capacitor-start, start-winding, and run-winding amps 90° apart.

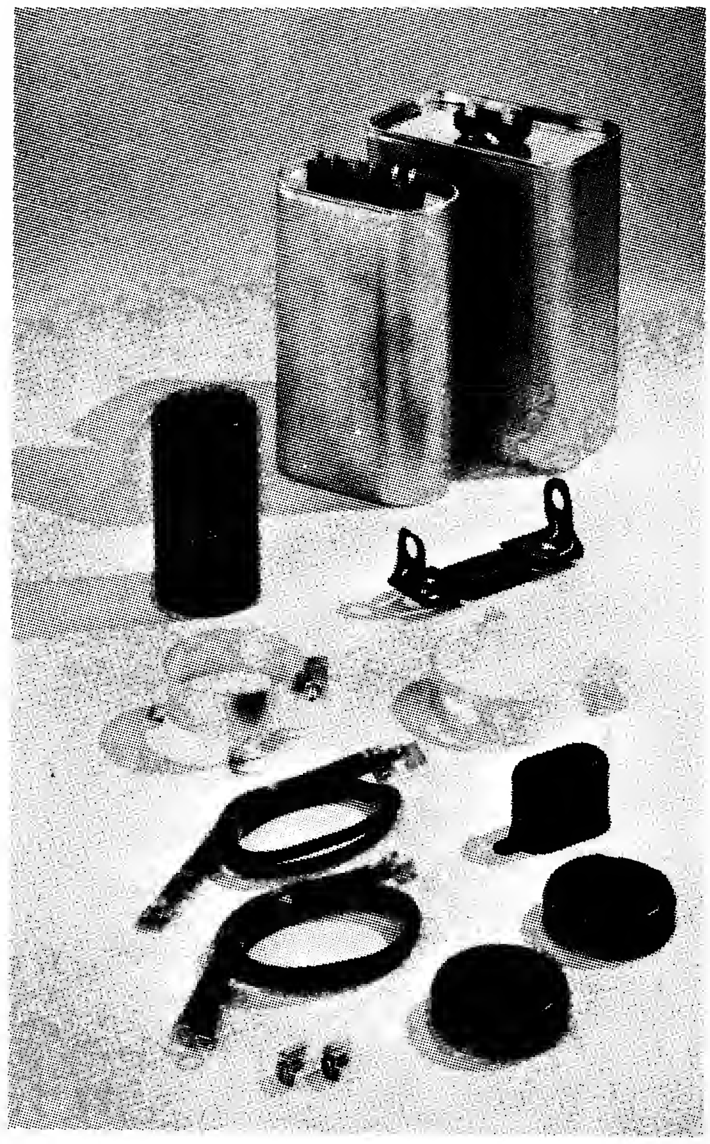


Fig. 1-38. AC capacitors with mounting hardware and accessories. *(P.R. Mallory & Co.)*

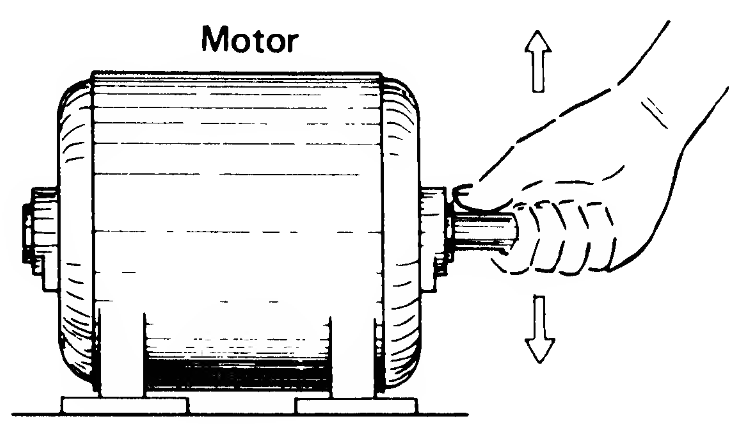


Fig. 1-39. The bearings are tested by trying to move the shaft vertically.

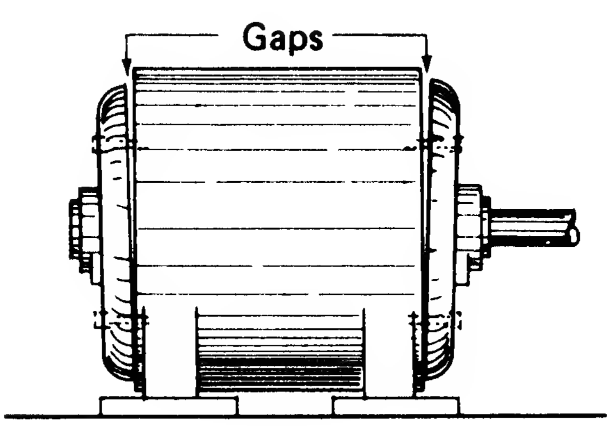


Fig. 1-40. A motor showing end plates not mounted properly. This prevents the rotor from turning. Use a mallet to tap plates into position.

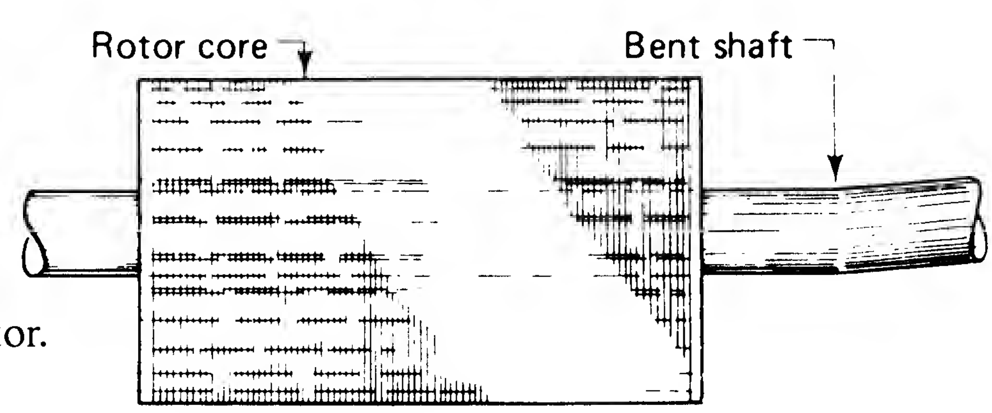
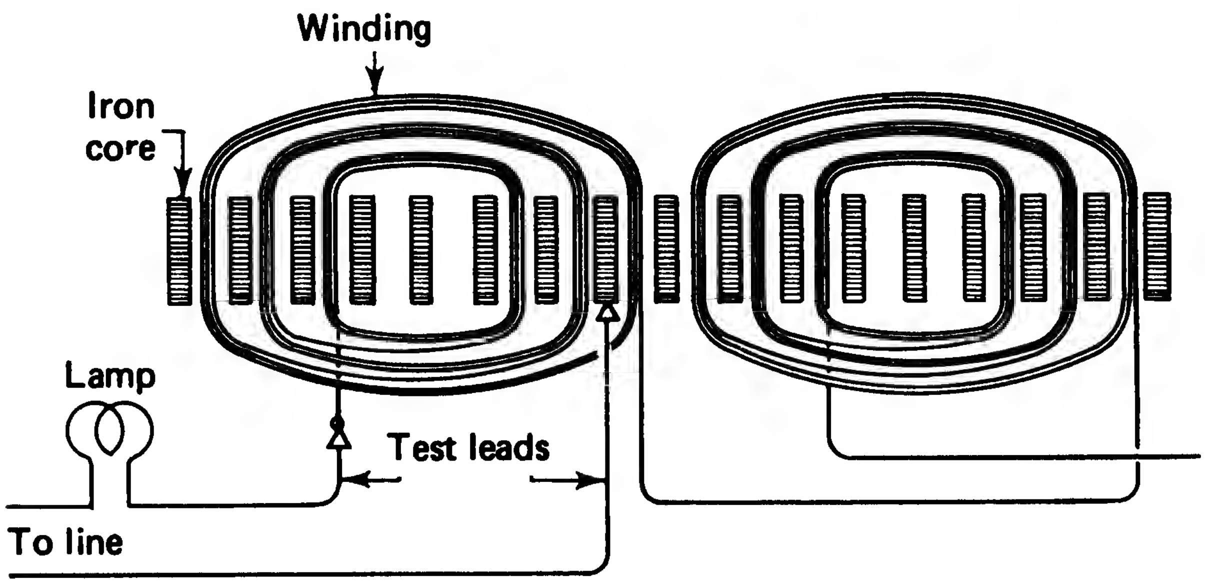
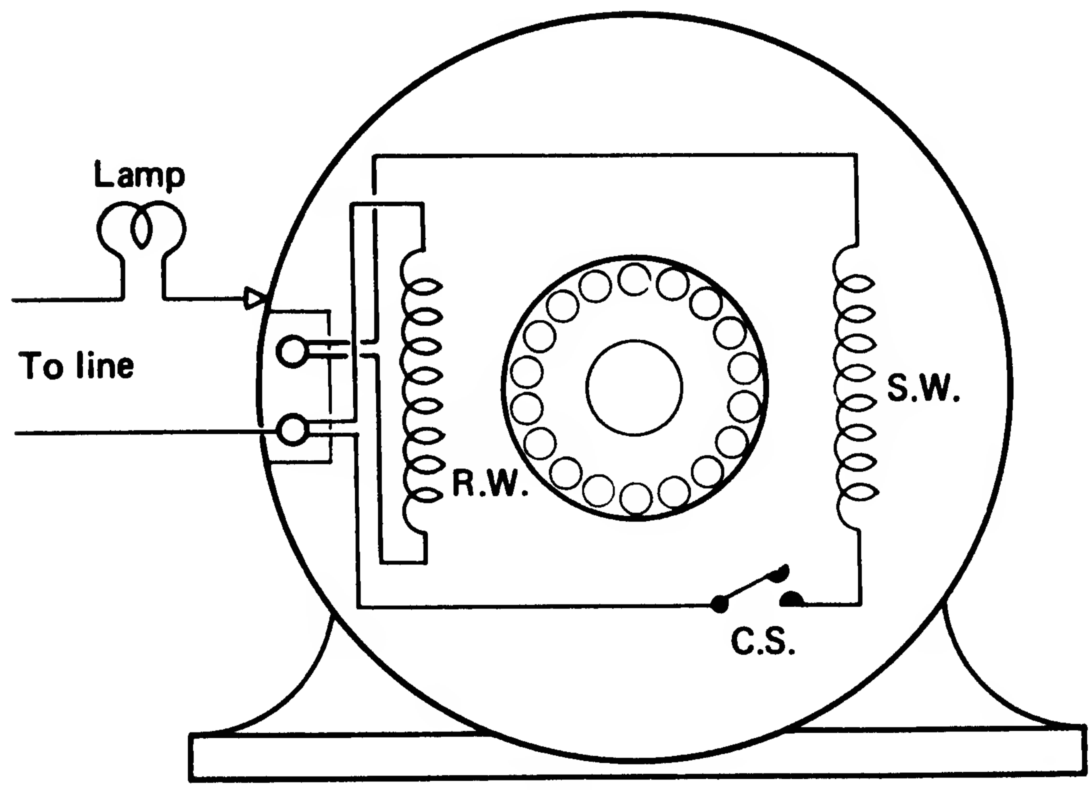


Fig. 1-41. The bent shaft of a rotor.



(A)



(B)

Fig. 1-42. To determine whether winding is grounded, connect one test lead to the winding and the other test lead to the core. The lighted lamp indicates a ground.

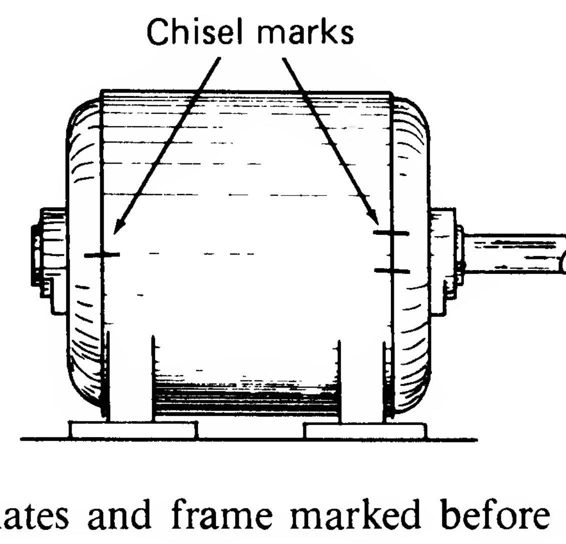


Fig. 1-43. End plates and frame marked before disassembling.

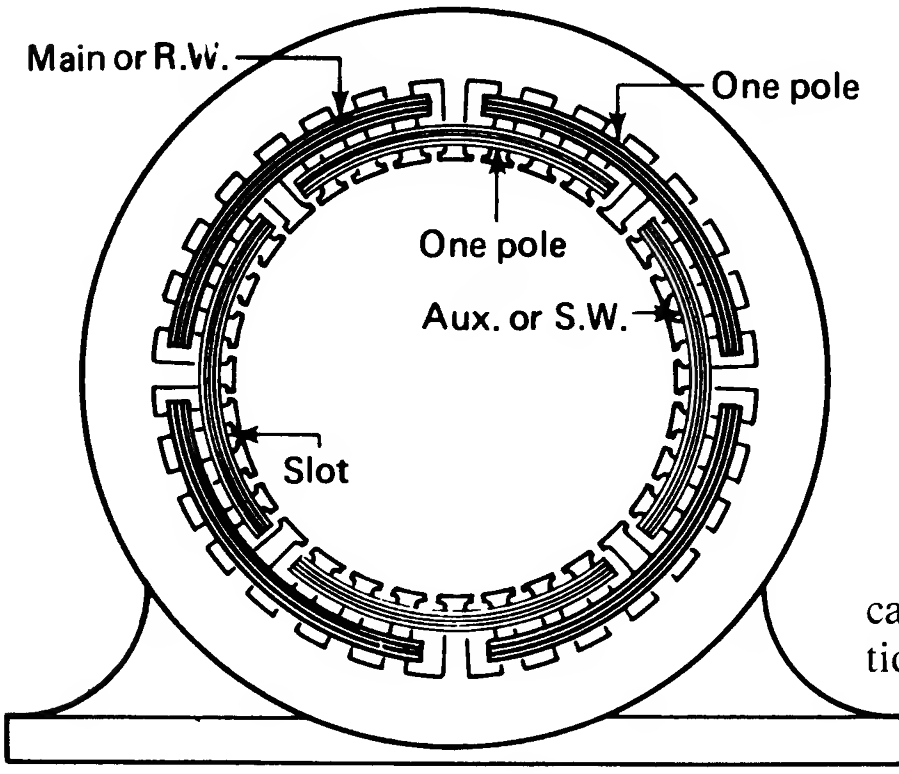


Fig. 1-44. The two windings of a capacitor-start motor. Note the four sections or poles in each winding.

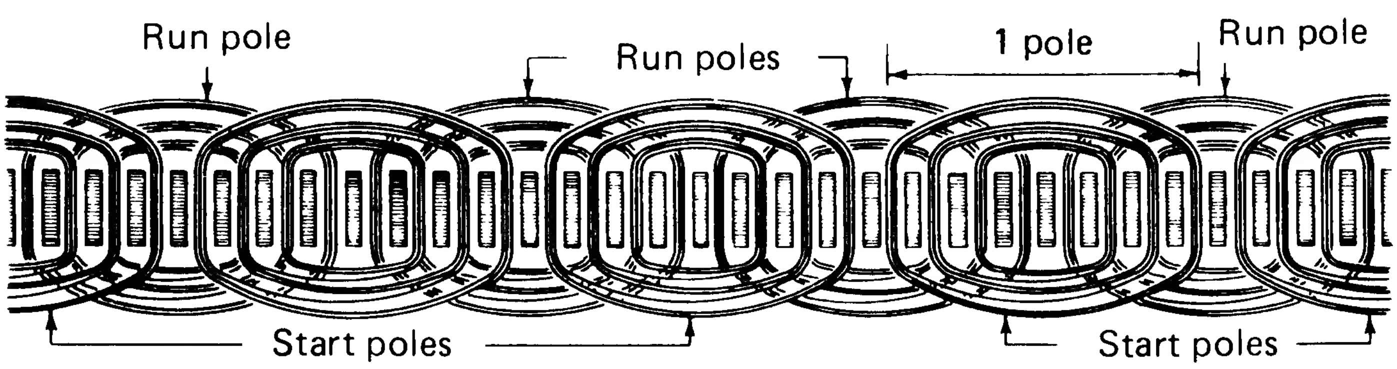


Fig. 1-45. A diagram of the stator in **Fig. 1-44** with slots and windings shown as they would look if rolled flat. The start winding poles are located between two running winding poles.

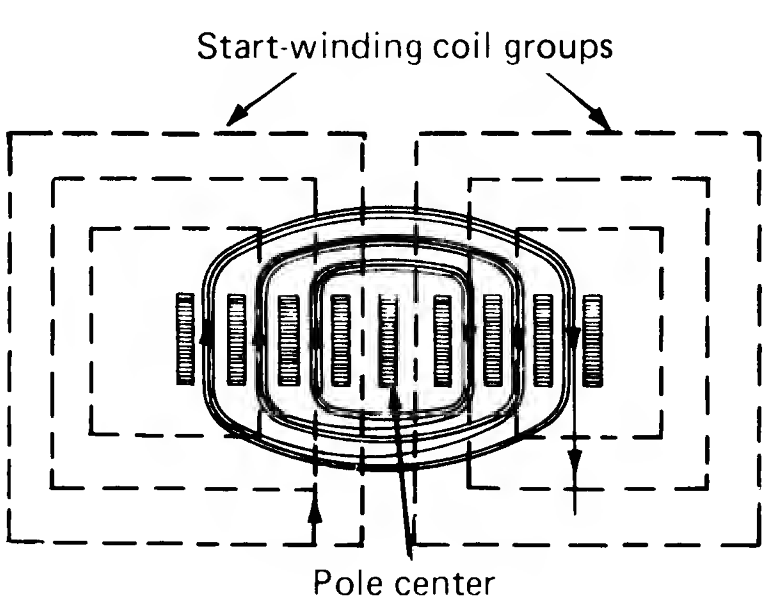


Fig. 1-46. The center of a pole forms in the teeth between two coil sides that have their currents flowing in opposite directions. This determines where the start-winding coils are placed.

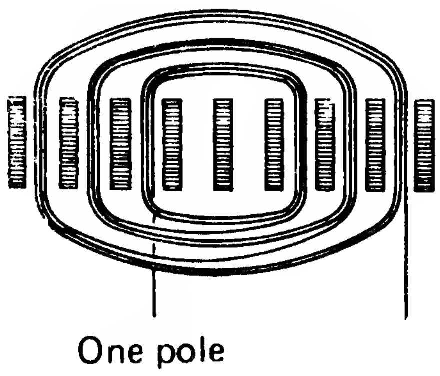


Fig. 1-47. Each pole consists of three coils, and each coil is wound in two slots separated by other slots.

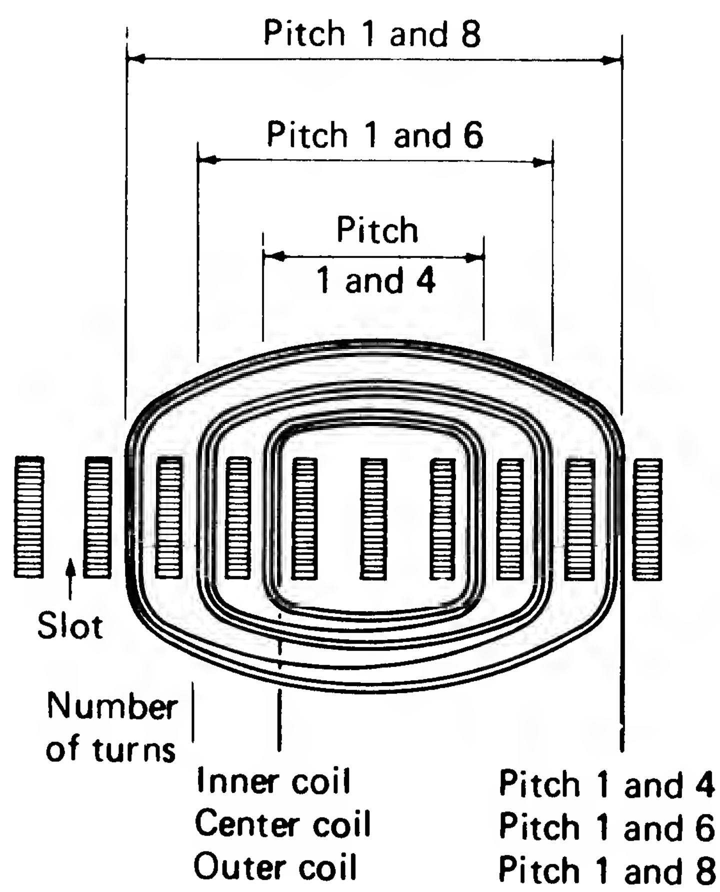


Fig. 1-48. The pitch, or span, of the three coils forming one pole.

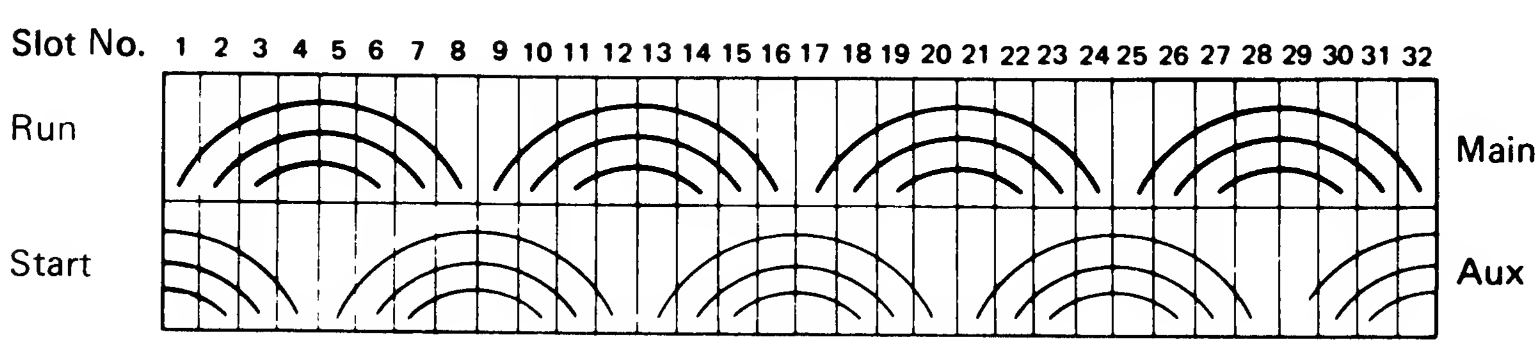


Fig. 1-49. The method of recording the pitch of the coils in a 32-slot, four-pole motor. The number of turns in each coil can be recorded alongside each coil in the diagram if so desired.

Figures 1-47; 1-48; 1-49

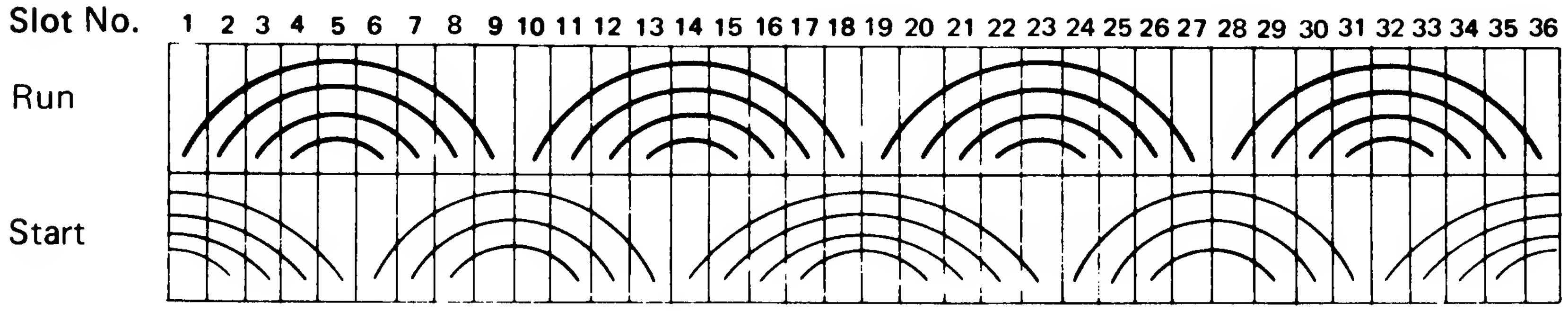


Fig. 1–50. Pitch data of a 36-slot, four-pole motor. The poles of the start winding are not the same; one pole has four coils, and the next has three.

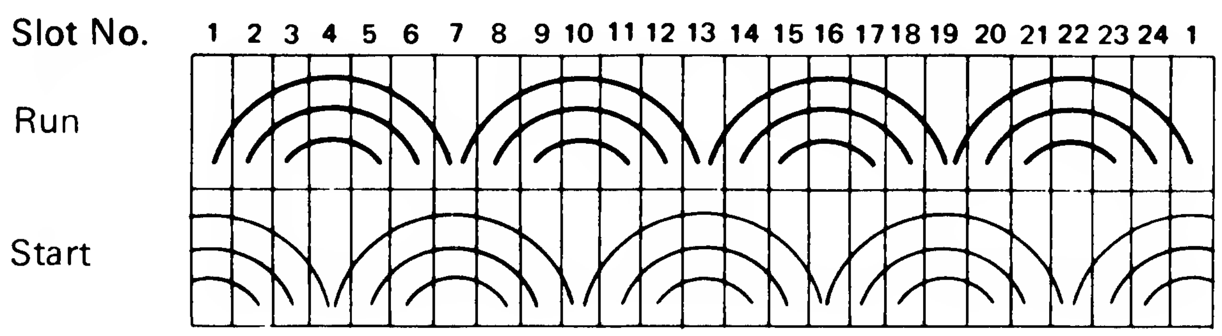


Fig. 1-51. Pitch data of a 24-slot, four-pole motor. The outer coils of adjacent poles are in the same slot.

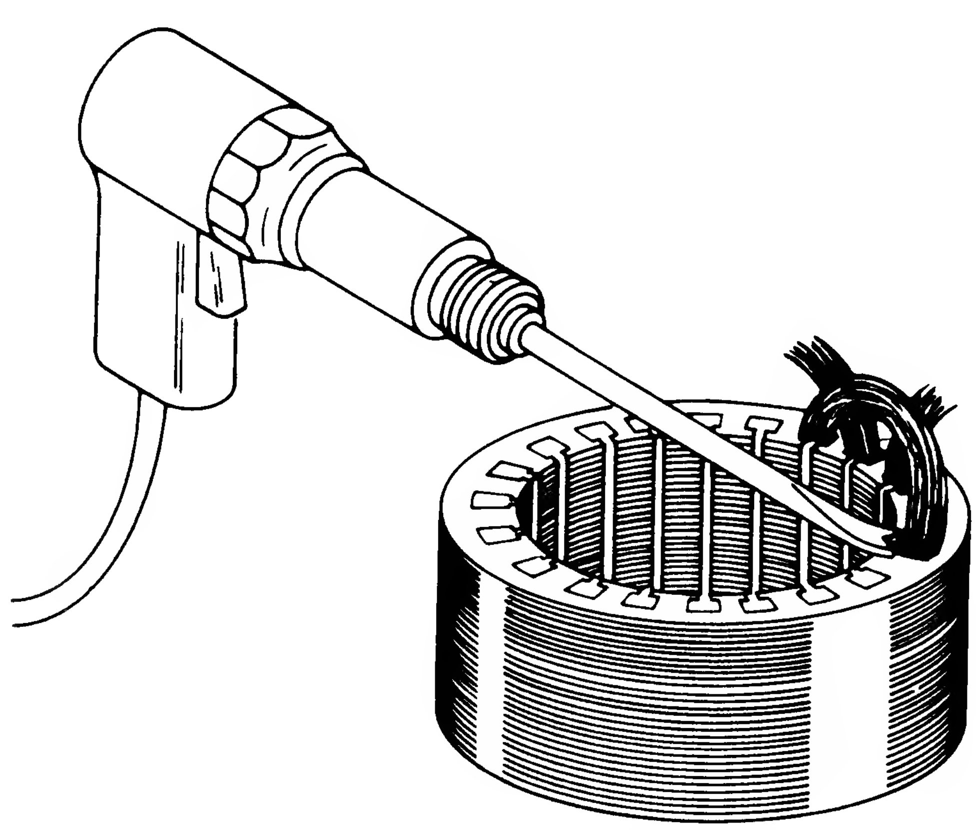


Fig. 1–52. Air chisel for stripping windings.

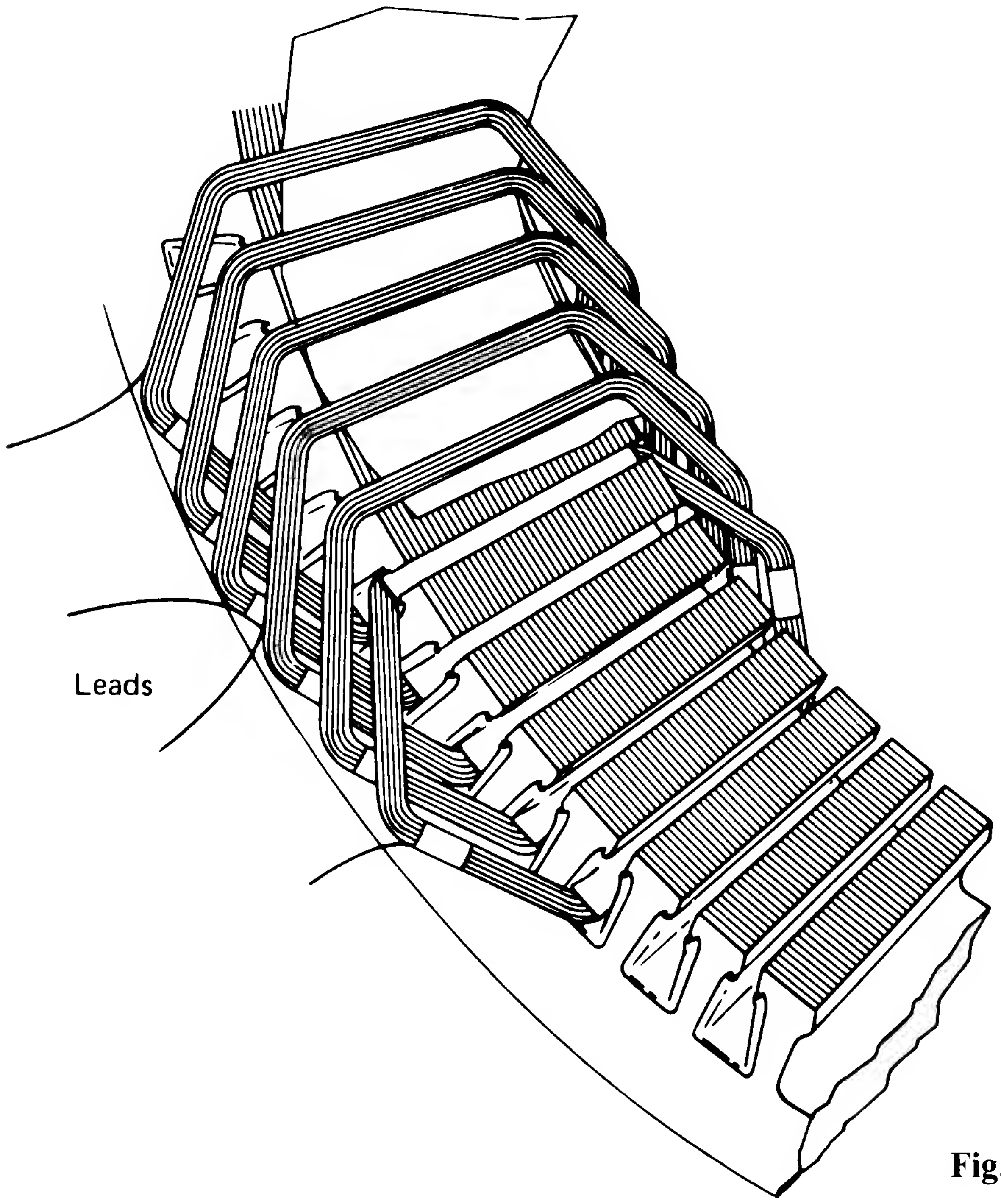


Fig. 1–53. Lap winding.

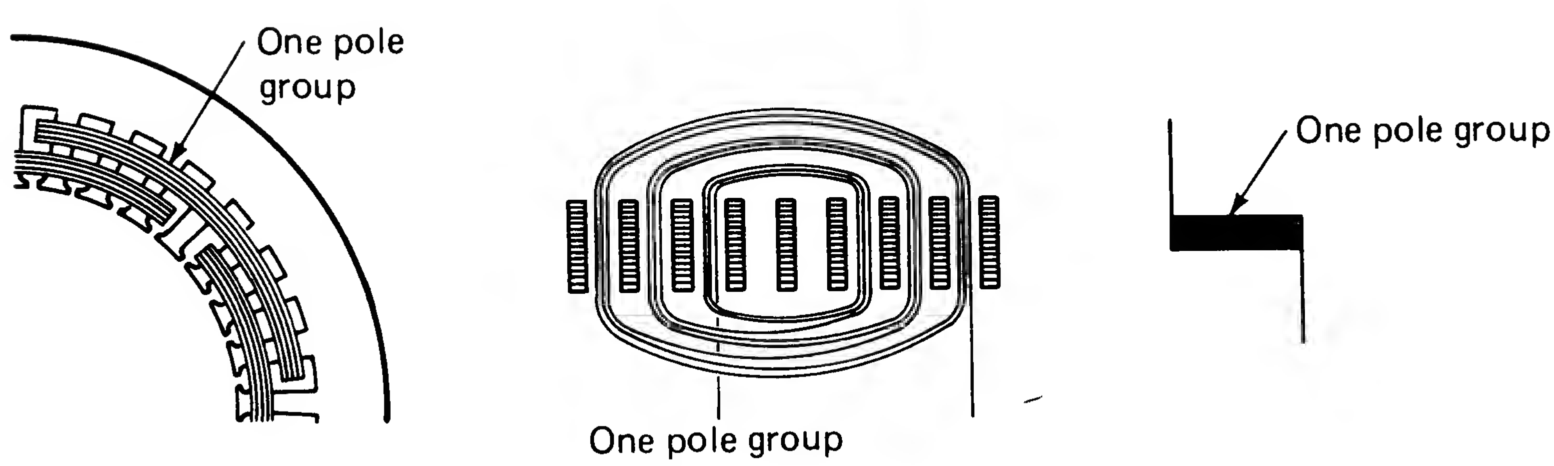


Fig. 1–54a. A pole group as it would appear in a stator (left), laid flat (center), and in a straight-line diagram (right).

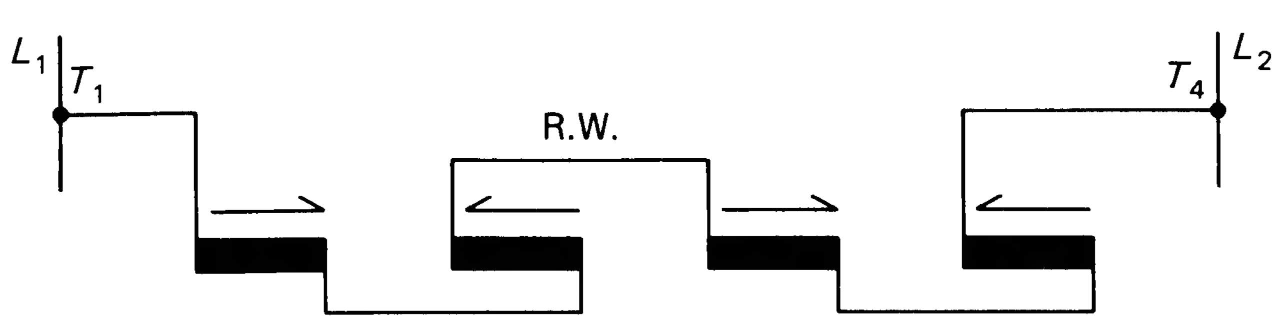


Fig. 1–54b. A four-pole, one-circuit, short jumper connection, showing the polarity of each coil. **Figs. 1–74** through **1–77** explain this illustration of run-winding poles.

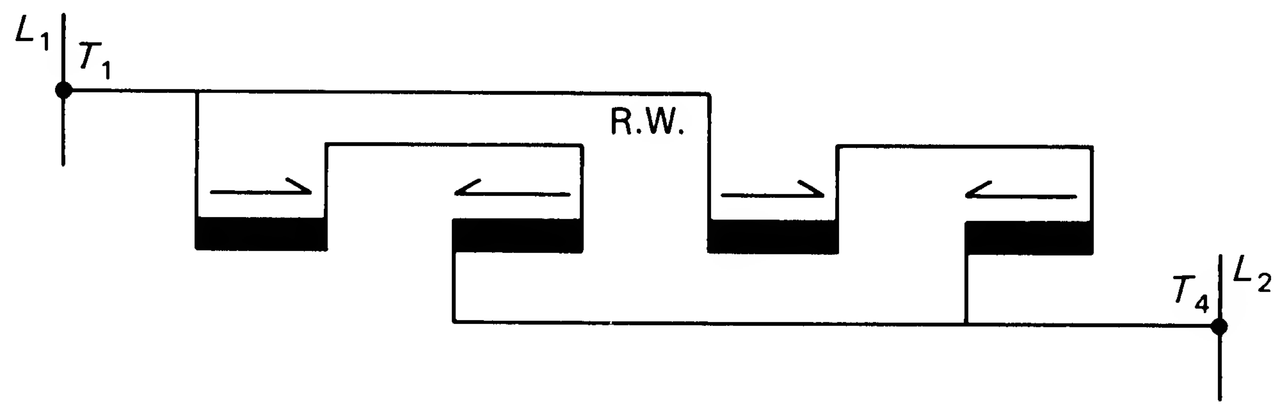


Fig. 1-55. A four-pole, two-circuit, short jumper connection.

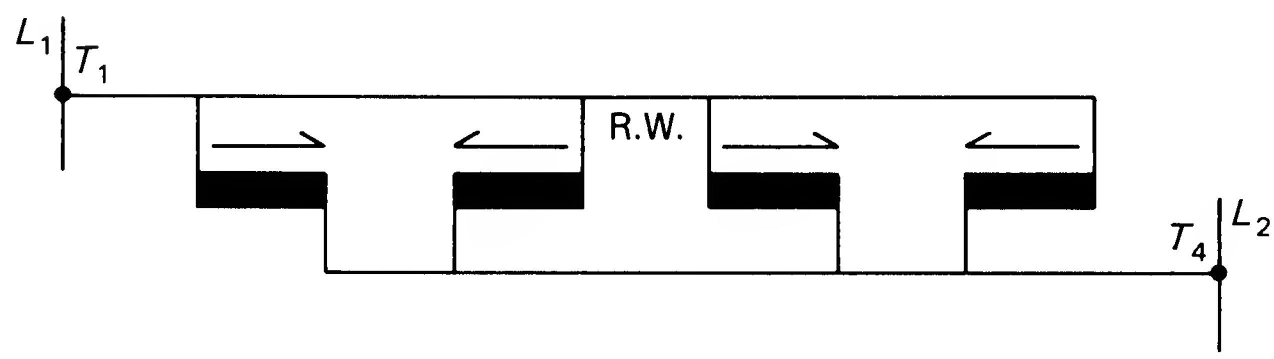


Fig. 1-56. A four-pole, four-circuit connection.

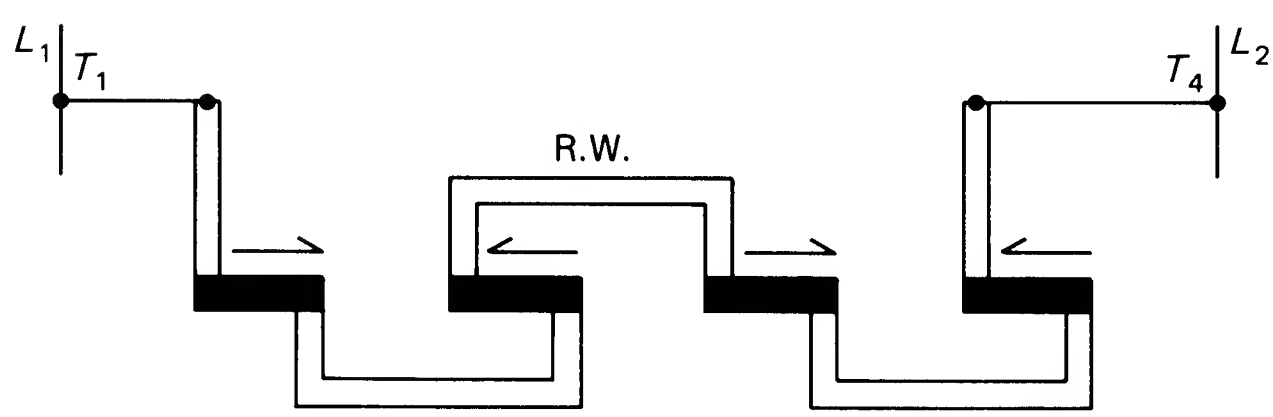


Fig. 1-57. A four-pole, one-circuit, short jumper connection wound with two wires. The coil groups are wound two in hand, and the wires are connected as one conductor with two strands.

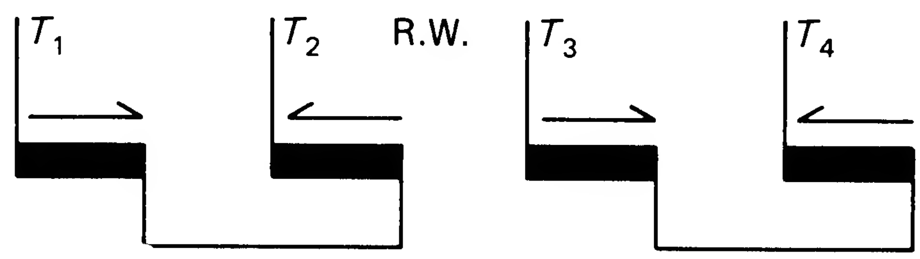


Fig. 1-58. A one- and two-circuit short jumper connection.

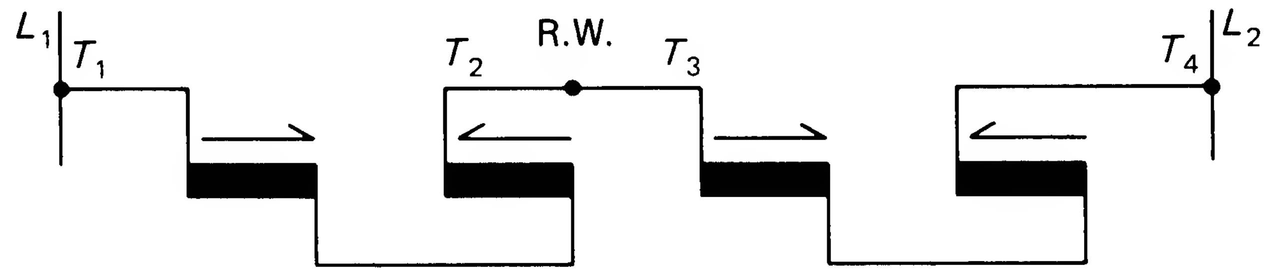


Fig. 1-59. A one- and two-circuit short jumper connection connected in series for high voltage.

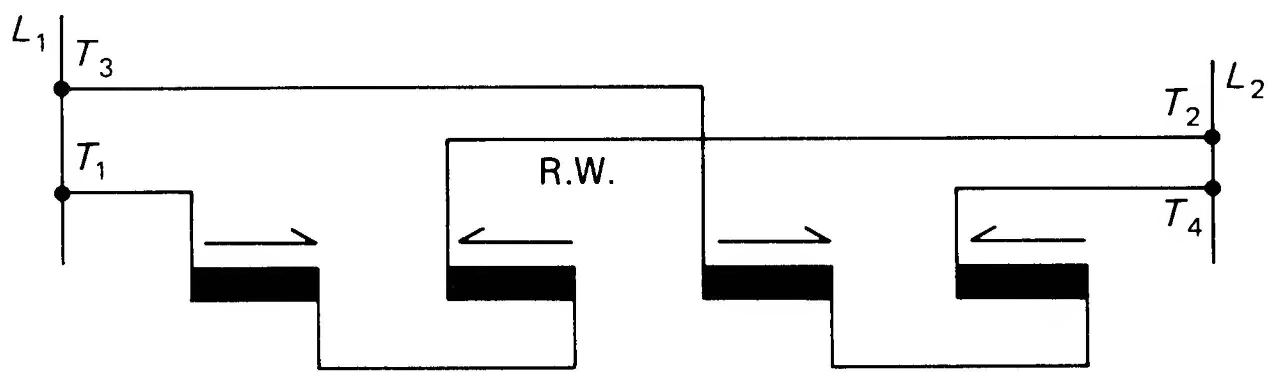


Fig. 1-60. A one- and two-circuit short jumper connection connected in parallel for low voltage.

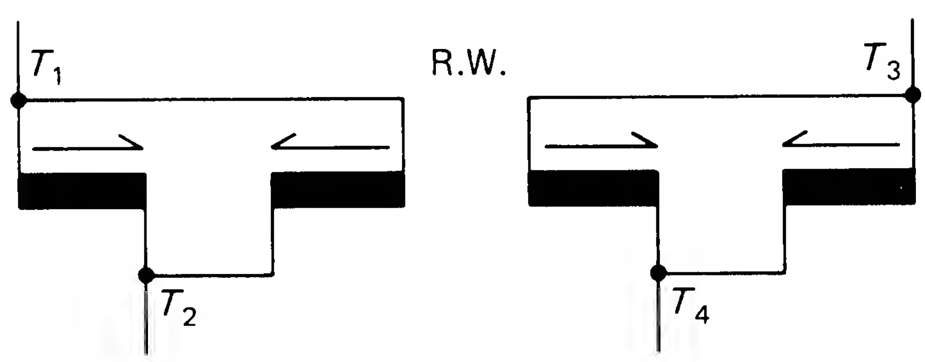


Fig. 1-61. A two- and four-circuit short jumper connection.

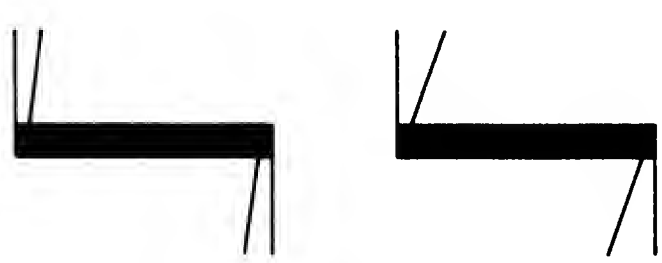


Fig. 1-62. Two-circuit coil groups wound two in hand, as they would appear in a motor.

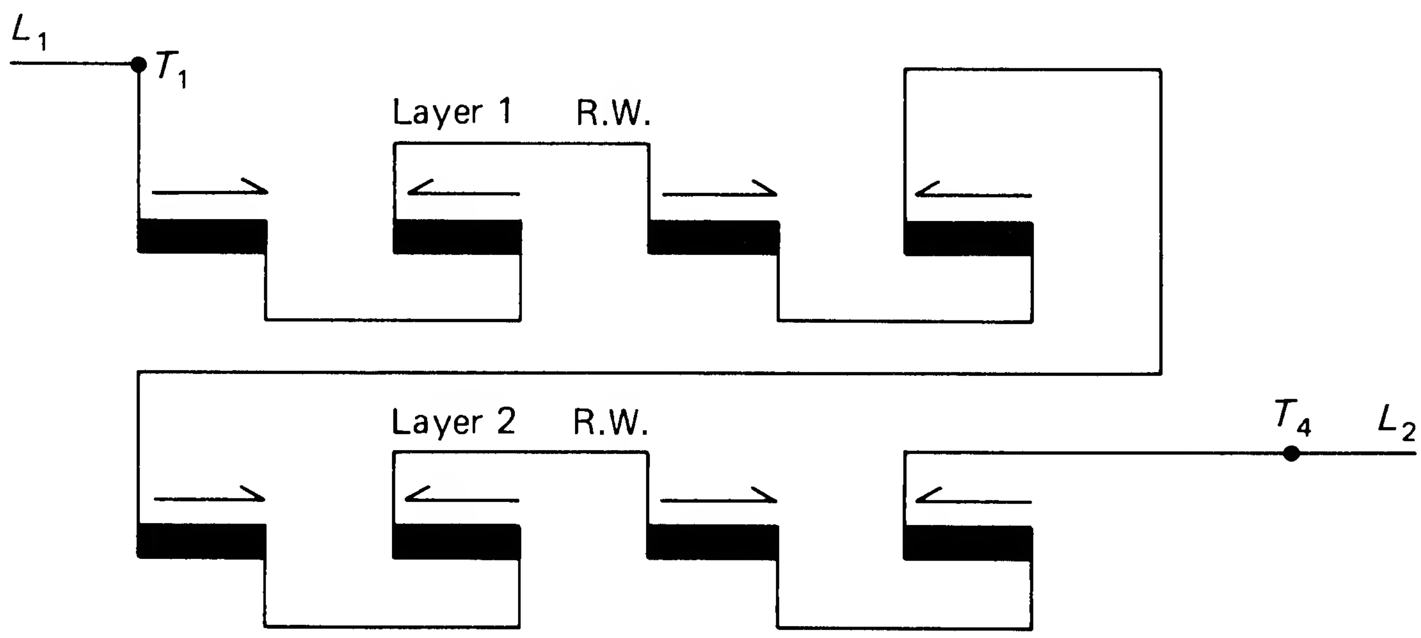


Fig. 1-63. A one-circuit, two-layer connection.

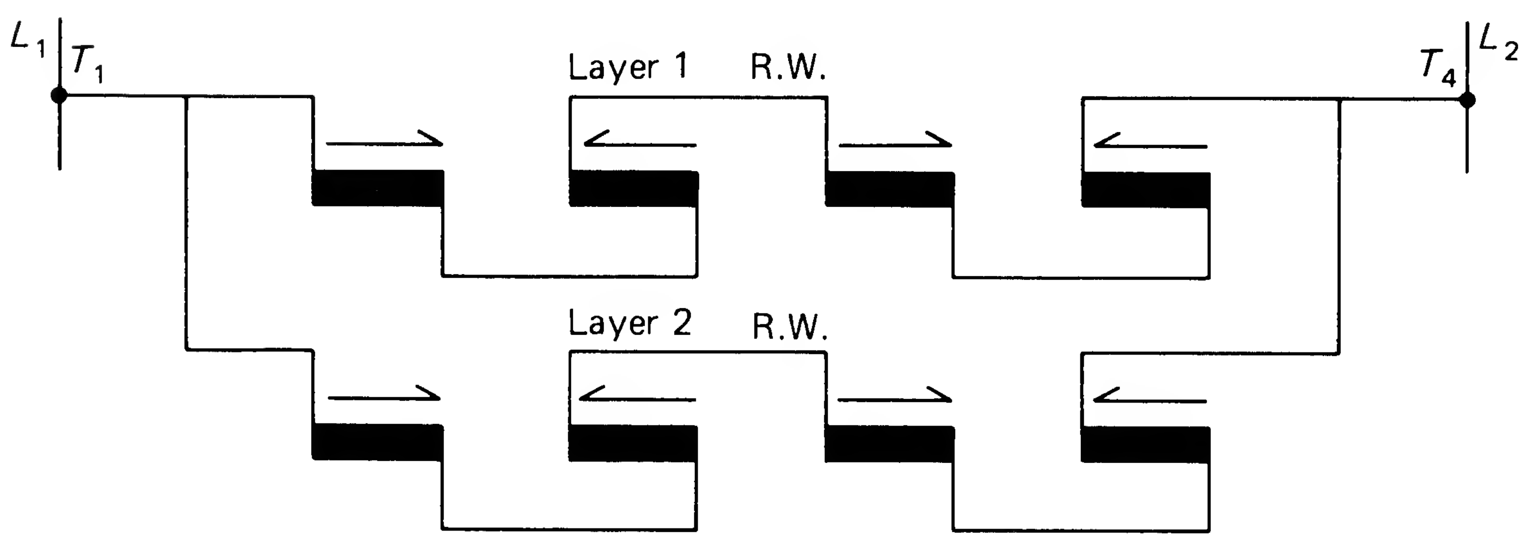


Fig. 1-64. A two-circuit, two-layer connection.

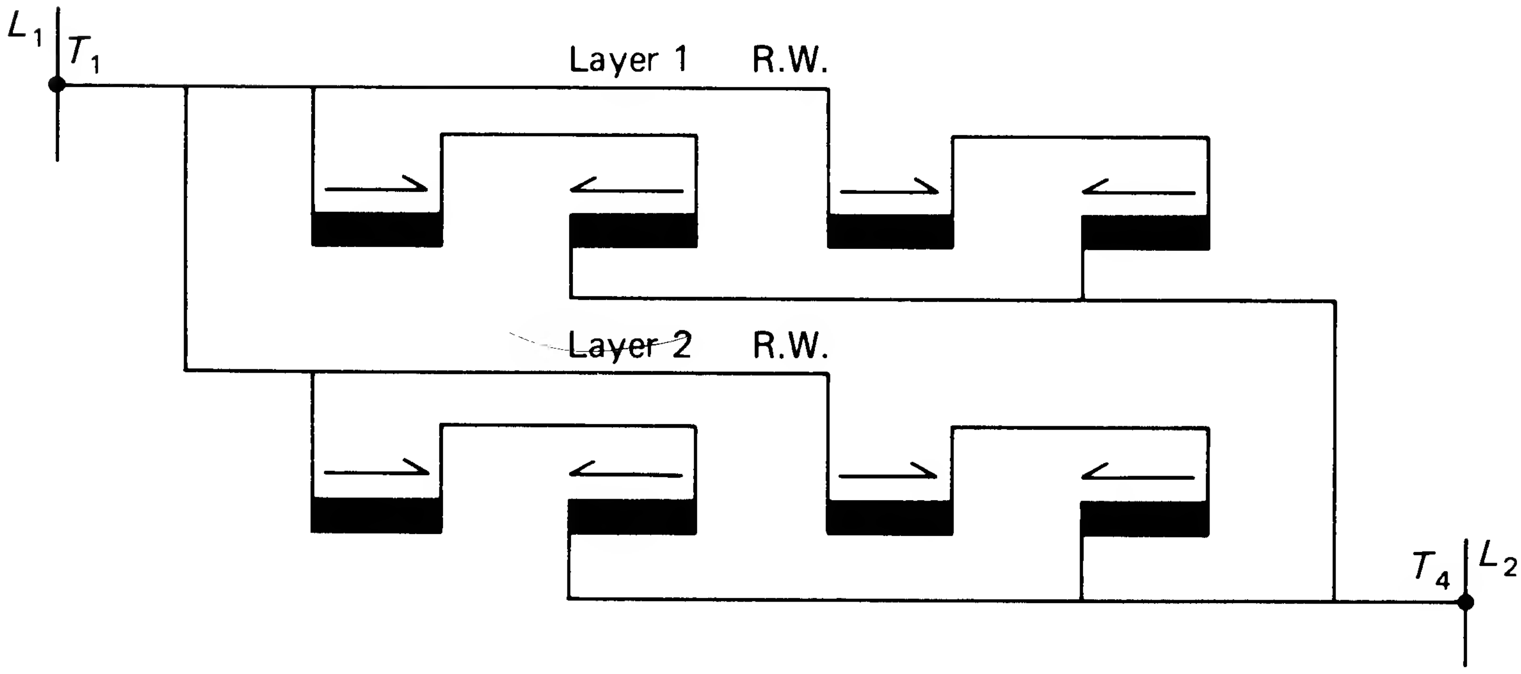


Fig. 1-65. A four-circuit, two-layer connection.

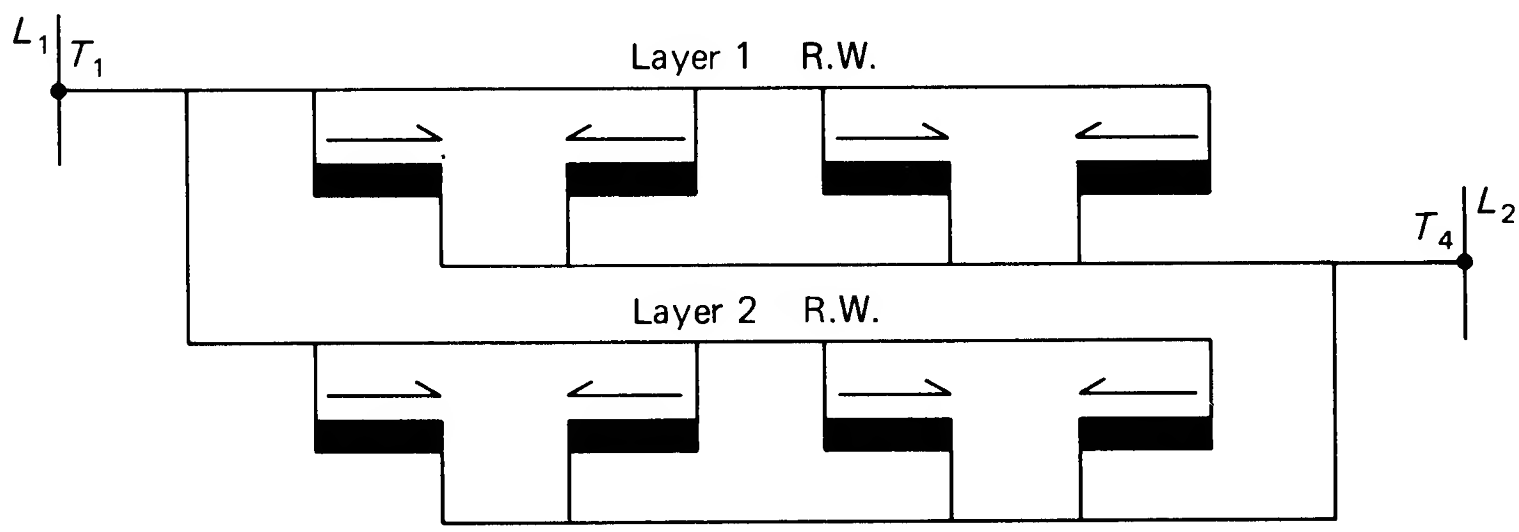


Fig. 1-66. An eight-circuit, two-layered connection.

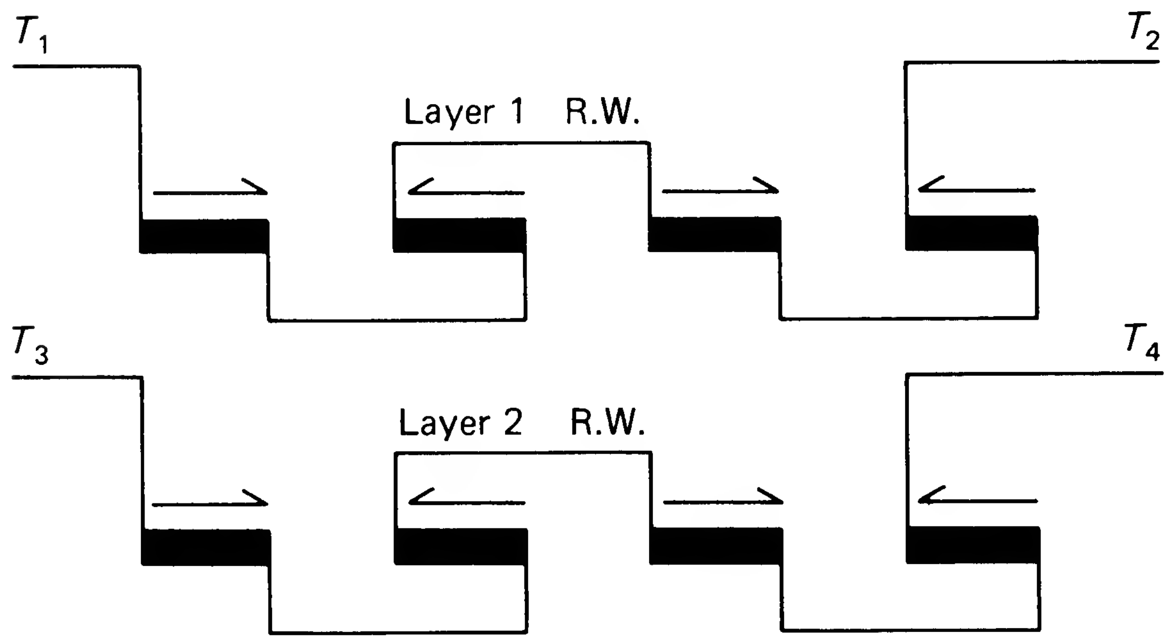


Fig. 1-67. A one- and two-circuit, two-layered connection.

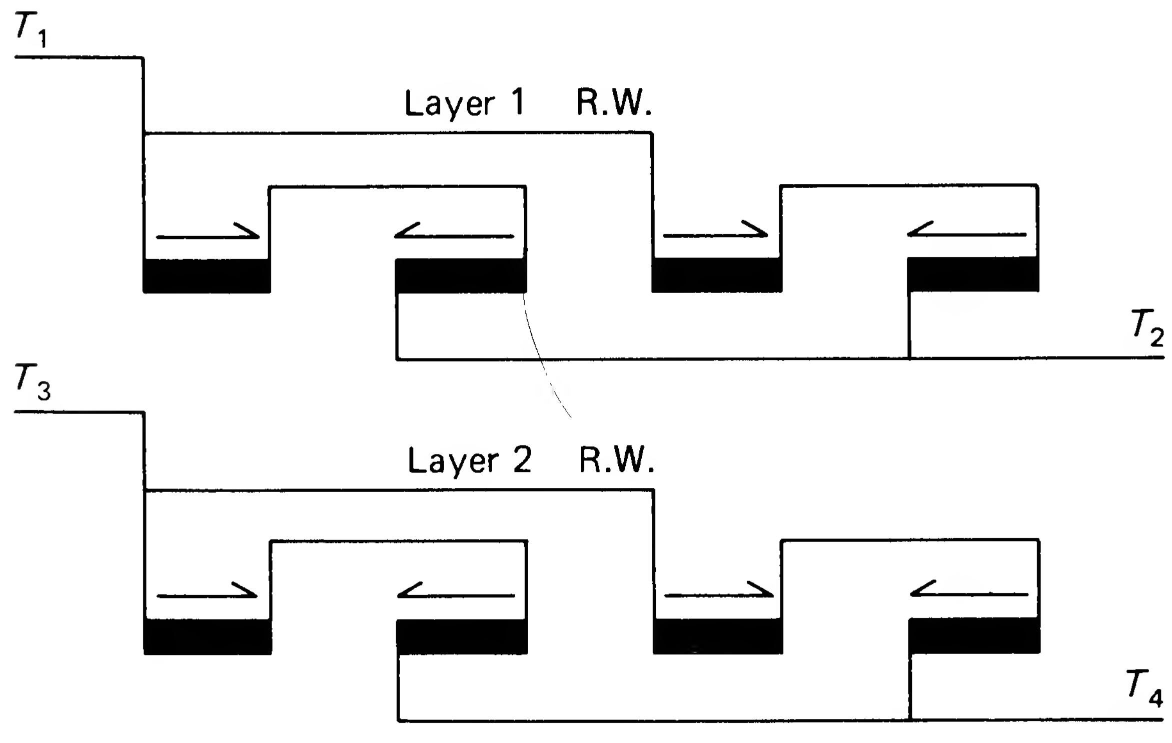


Fig. 1-68. A two- and four-circuit, two-layered connection.

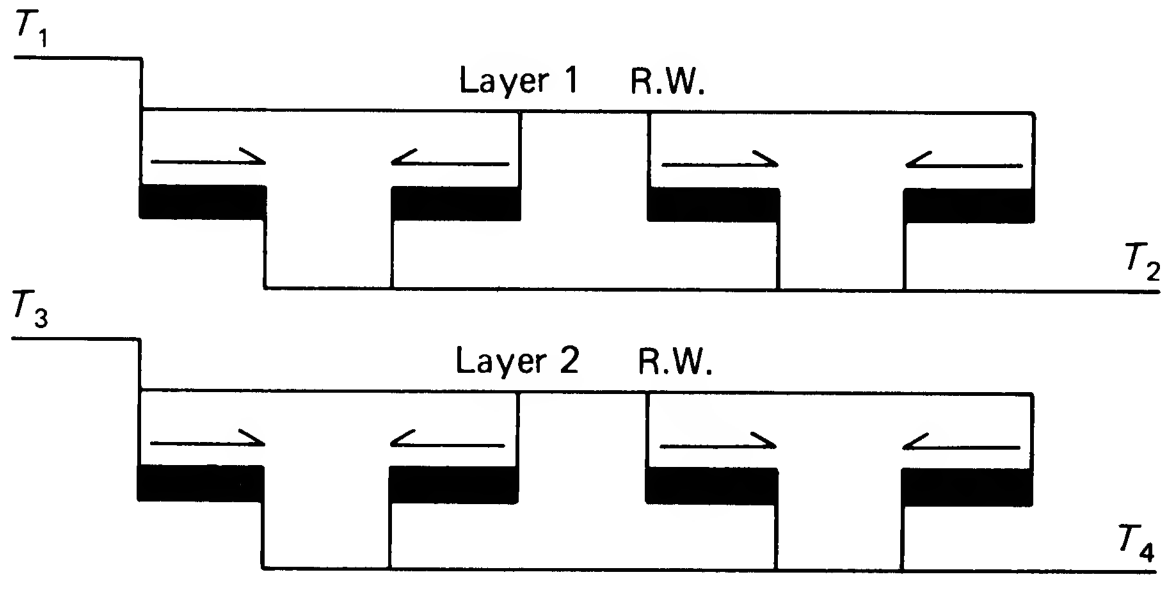


Fig. 1-69. A four- and eight-circuit, two-layered connection.

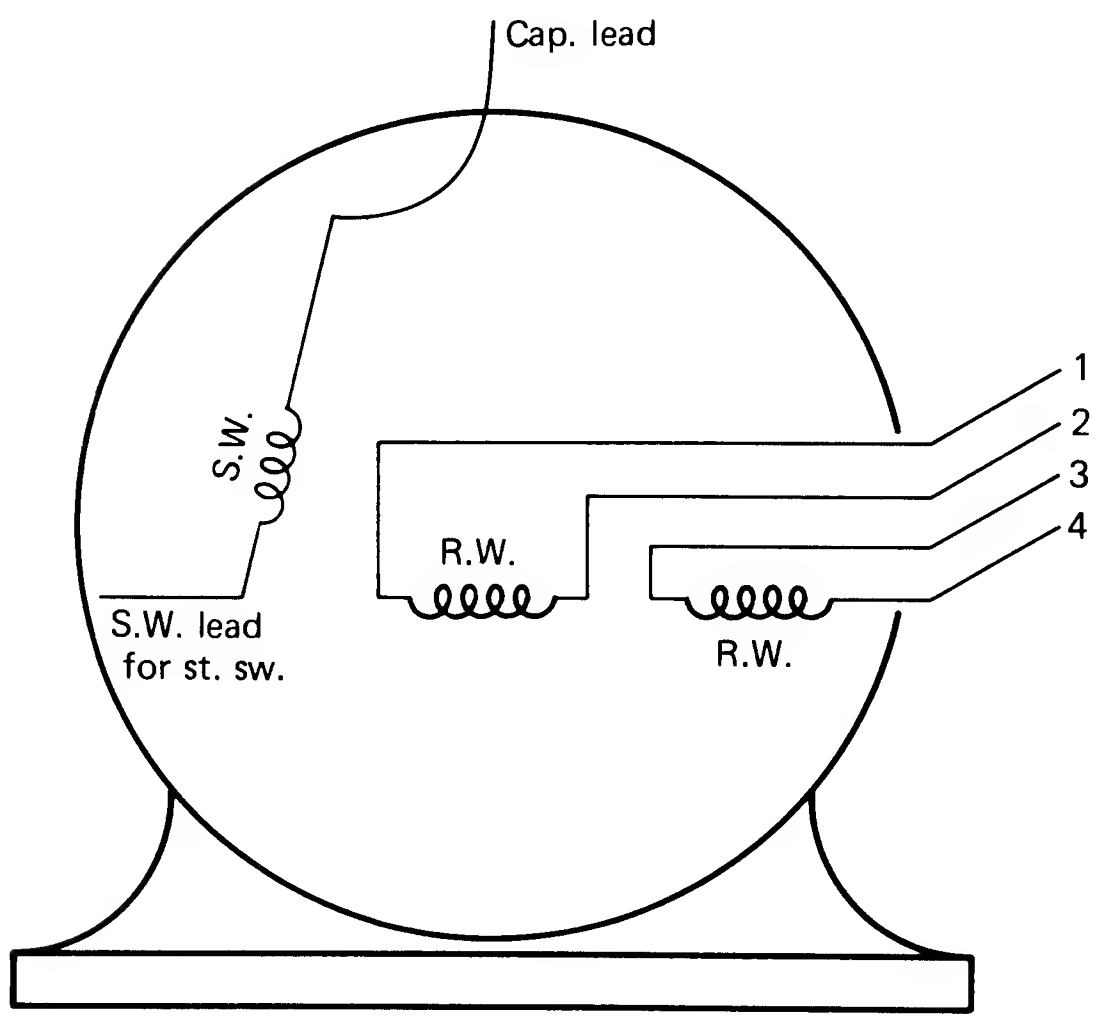


Fig. 1-70. Sketch of stator as done by the repairperson to show where the leads should be brought out of the stator when the rewind is completed and the leads are tied down. The start switch is on the left side, and so a start-winding lead is tied down at that spot. One start lead goes to the capacitor, and the run leads go out the right side of the motor.

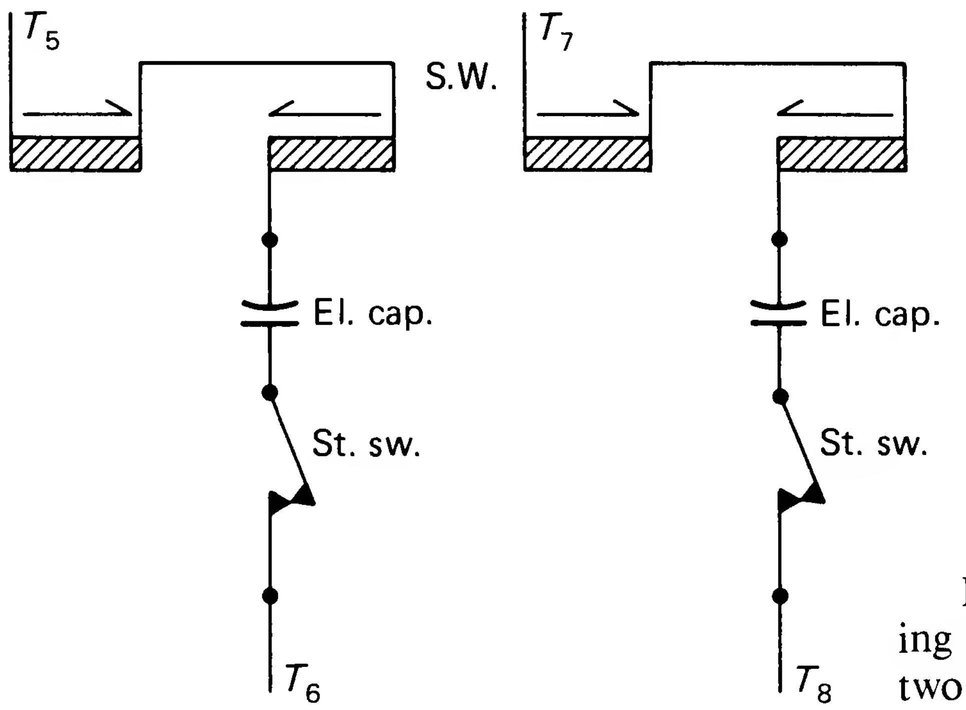


Fig. 1–71. A two-voltage start winding with two electrolytic capacitors and two switches.

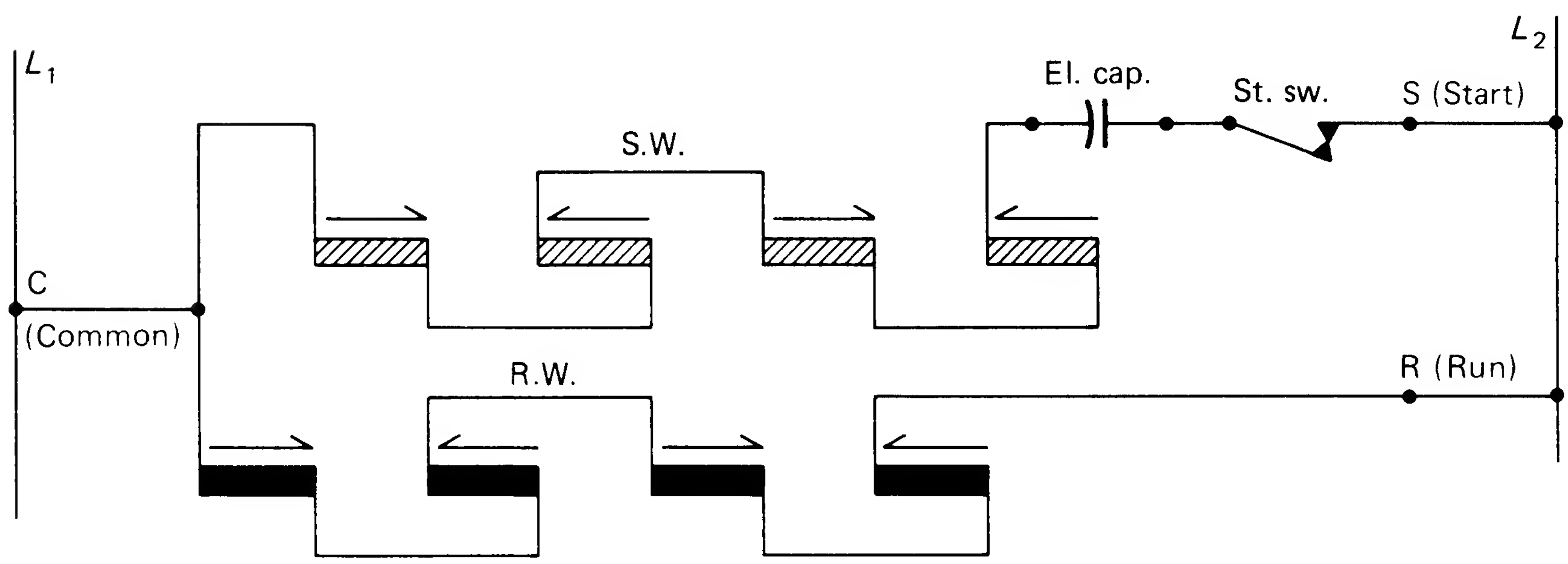


Fig. 1–72. A three-lead predetermined rotation connection found in sealed refrigeration compressors and submersible pumps. The switch and capacitors can be located separately from the motor.

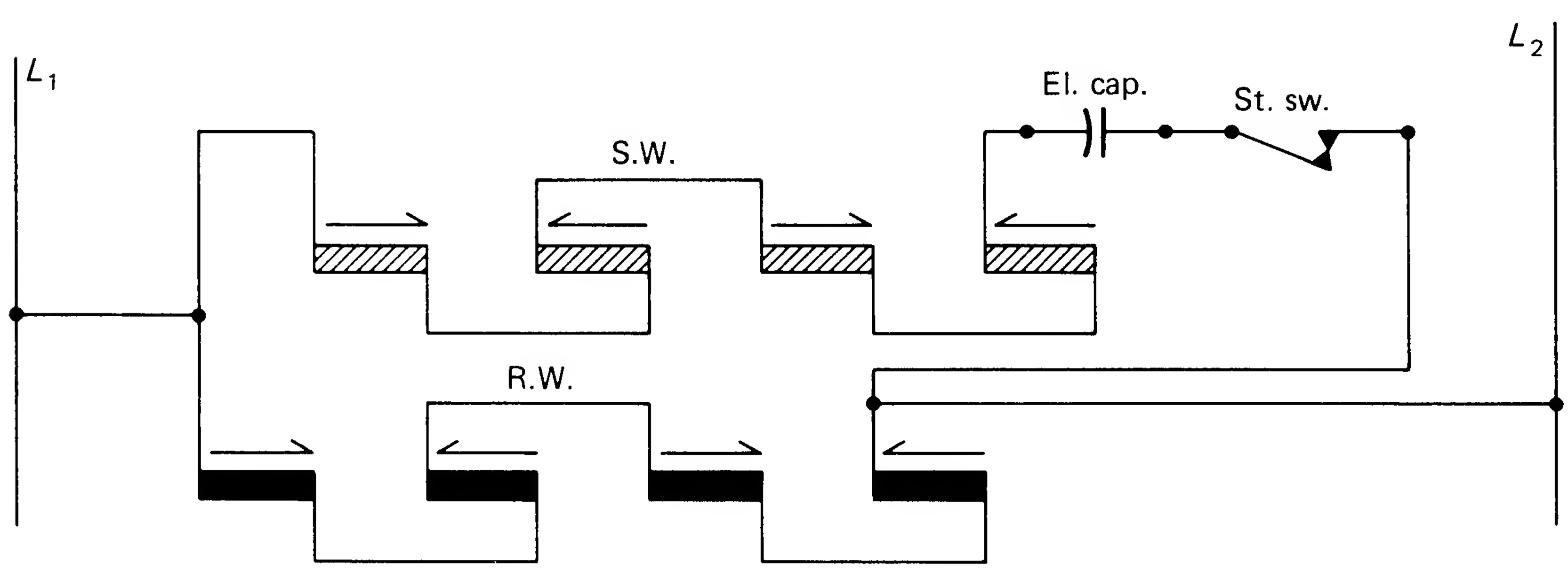


Fig. 1–73. A two-lead motor with the start winding connected internally.

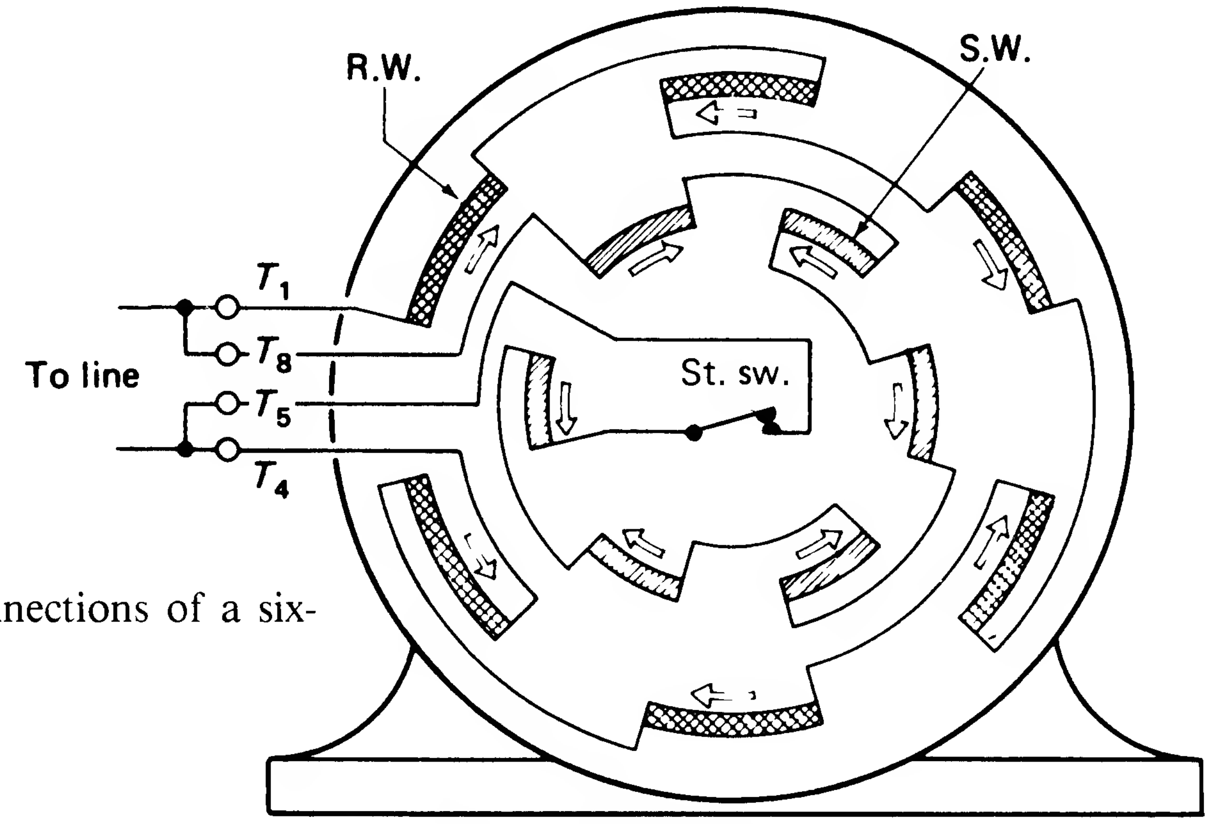


Fig. 1–74. The connections of a six-pole split-phase motor.

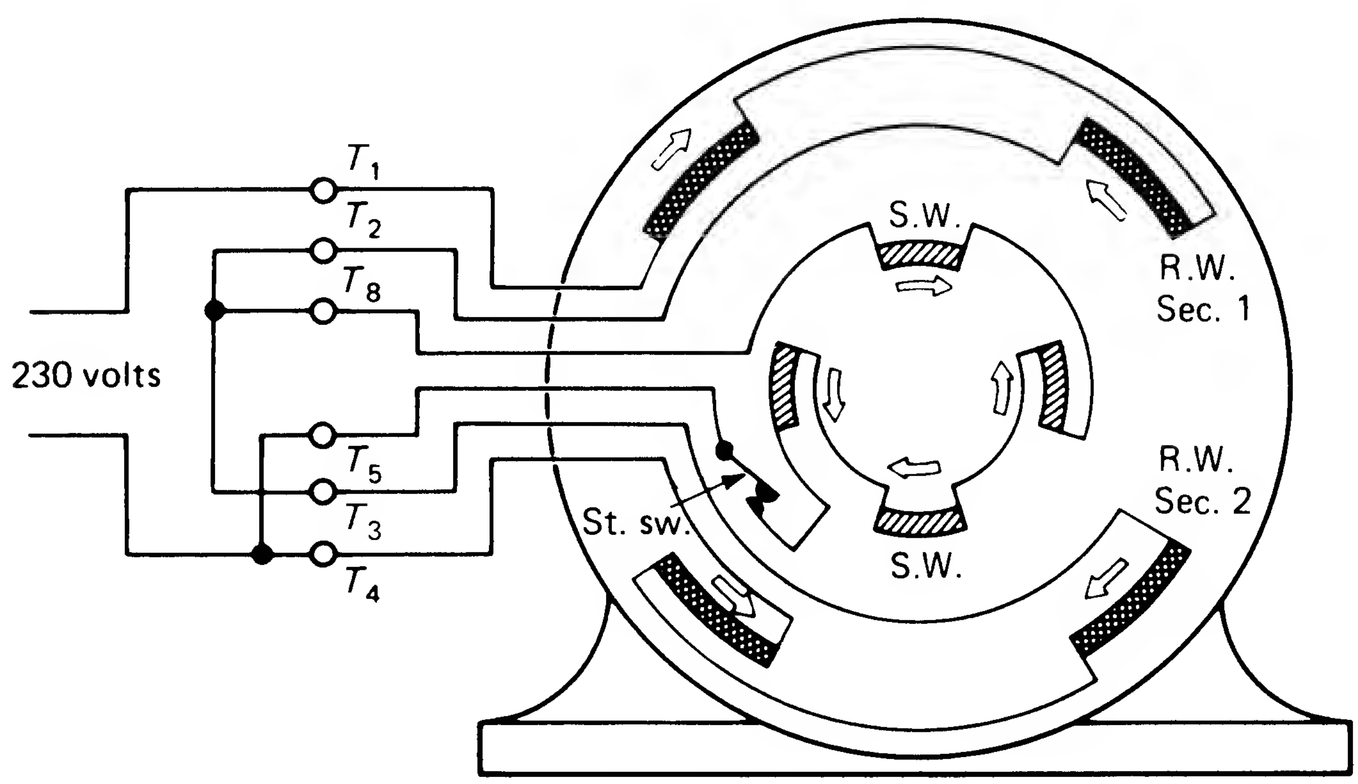


Fig. 1–75a. Four-pole dual-voltage split-phase motor. Counterclockwise for 230 volts.

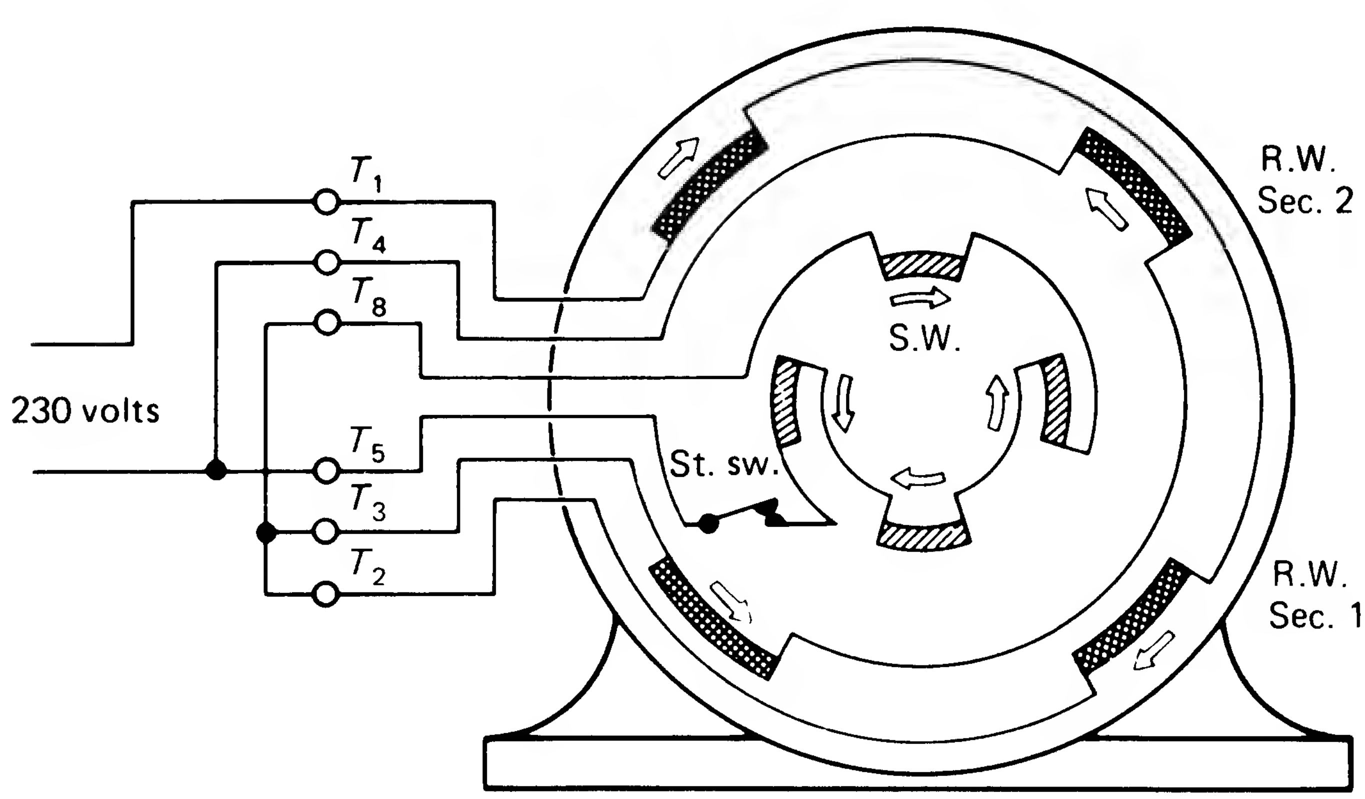


Fig. 1–75b. Four-pole dual-voltage split-phase motor—long jumper—counterclockwise for 230 volts.

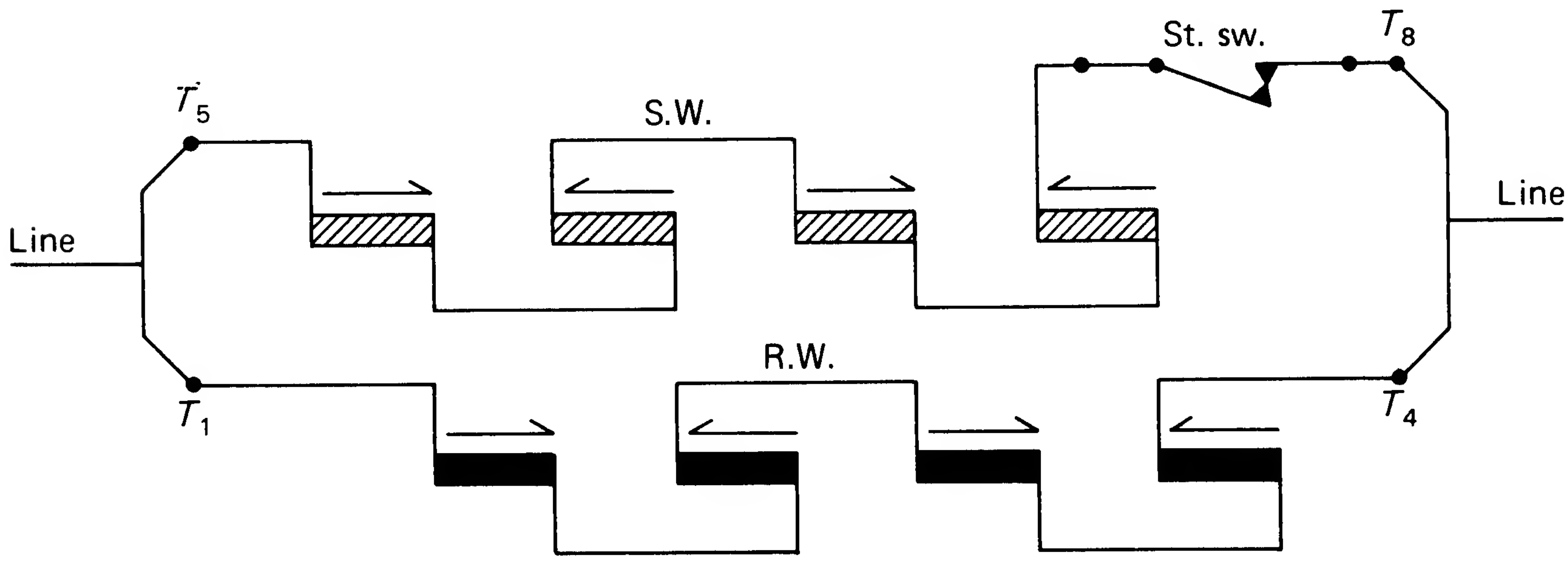


Fig. 1–76. Straight-line diagram of a split-phase motor connected with a short jumper.

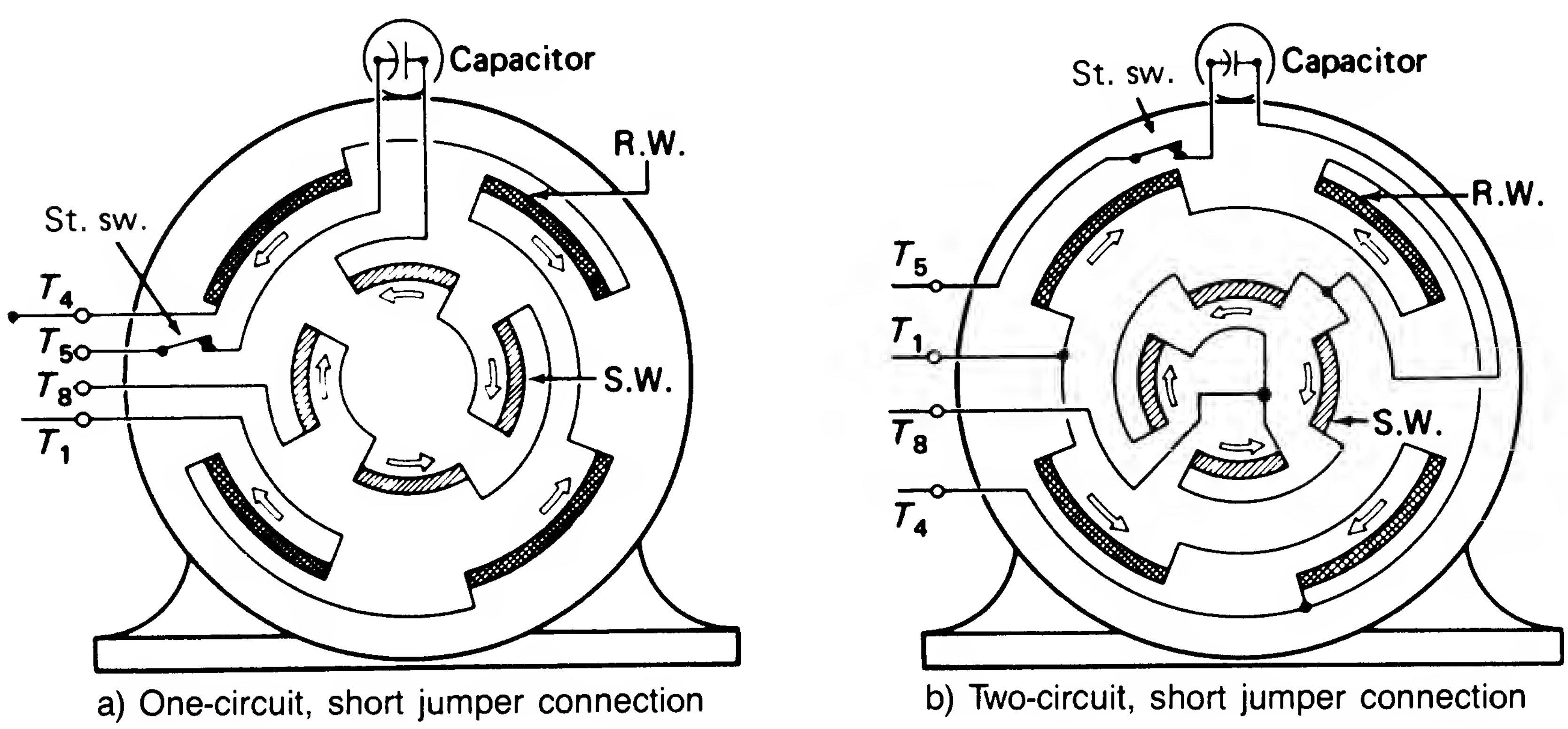


Fig. 1–77. (a) One-circuit and (b) two-circuit, short jumper connection.

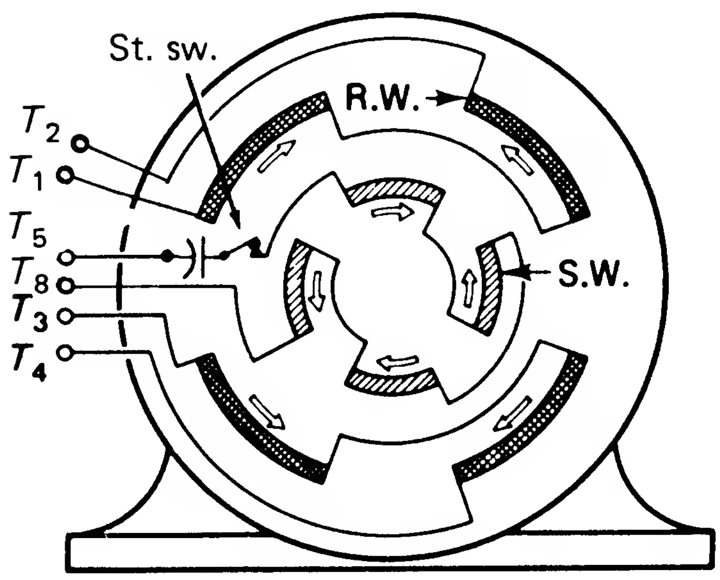


Fig. 1–78. A four-pole two-voltage motor diagram with short jumpers in the running winding.

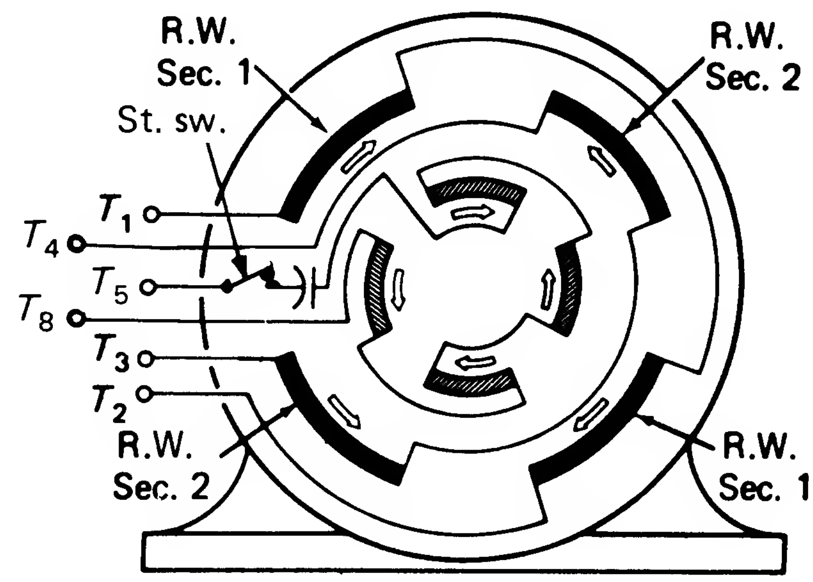


Fig. 1-79. A four-pole two-voltage motor with long jumper connections.

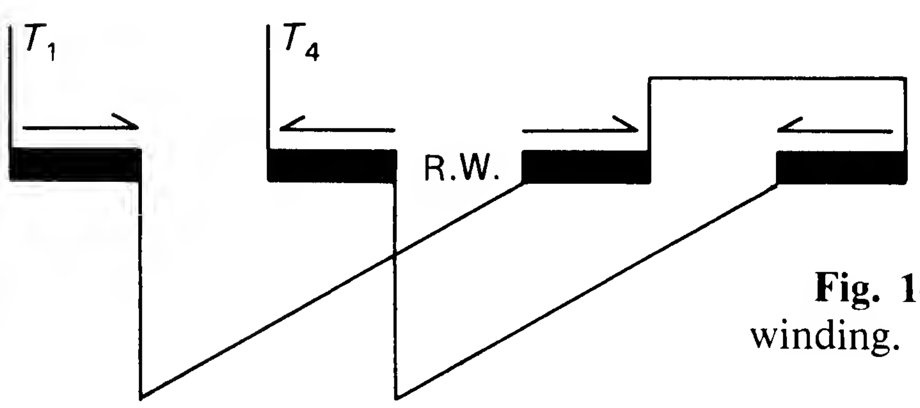


Fig. 1-80. One-circuit, long jumper run winding.

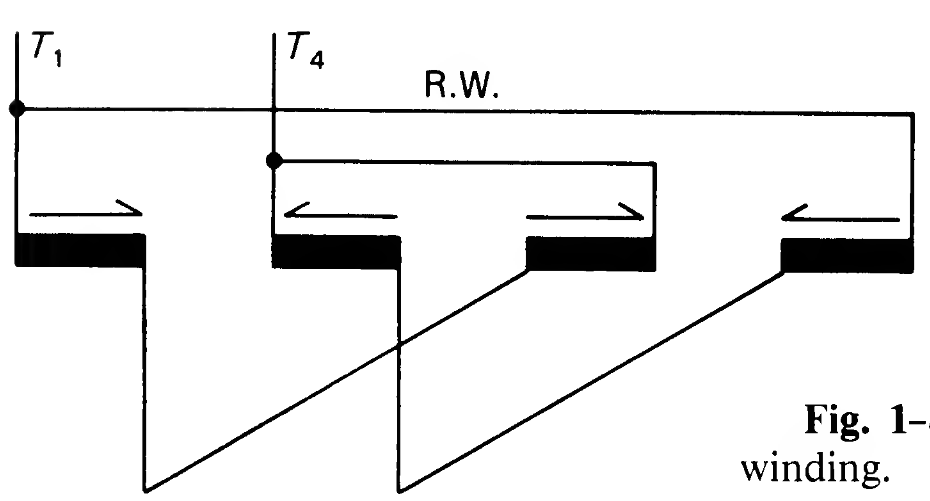


Fig. 1-81. Two-circuit, long jumper run winding.

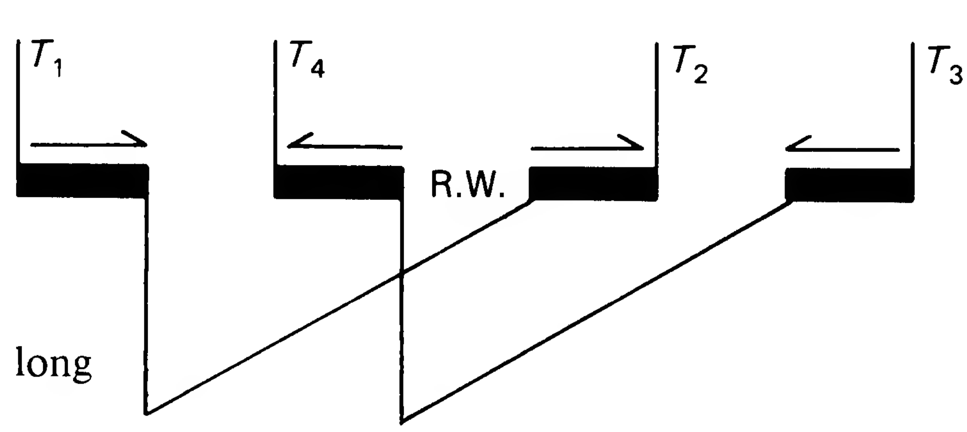


Fig. 1-82. One- and two-circuit, long jumper run winding.

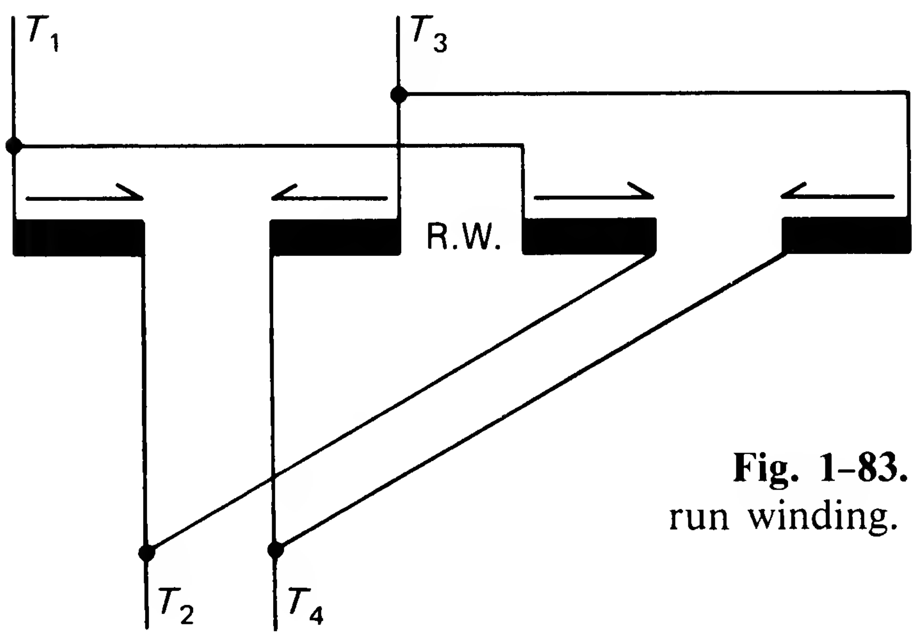


Fig. 1–83. Two- and four-circuit, long jumper run winding.

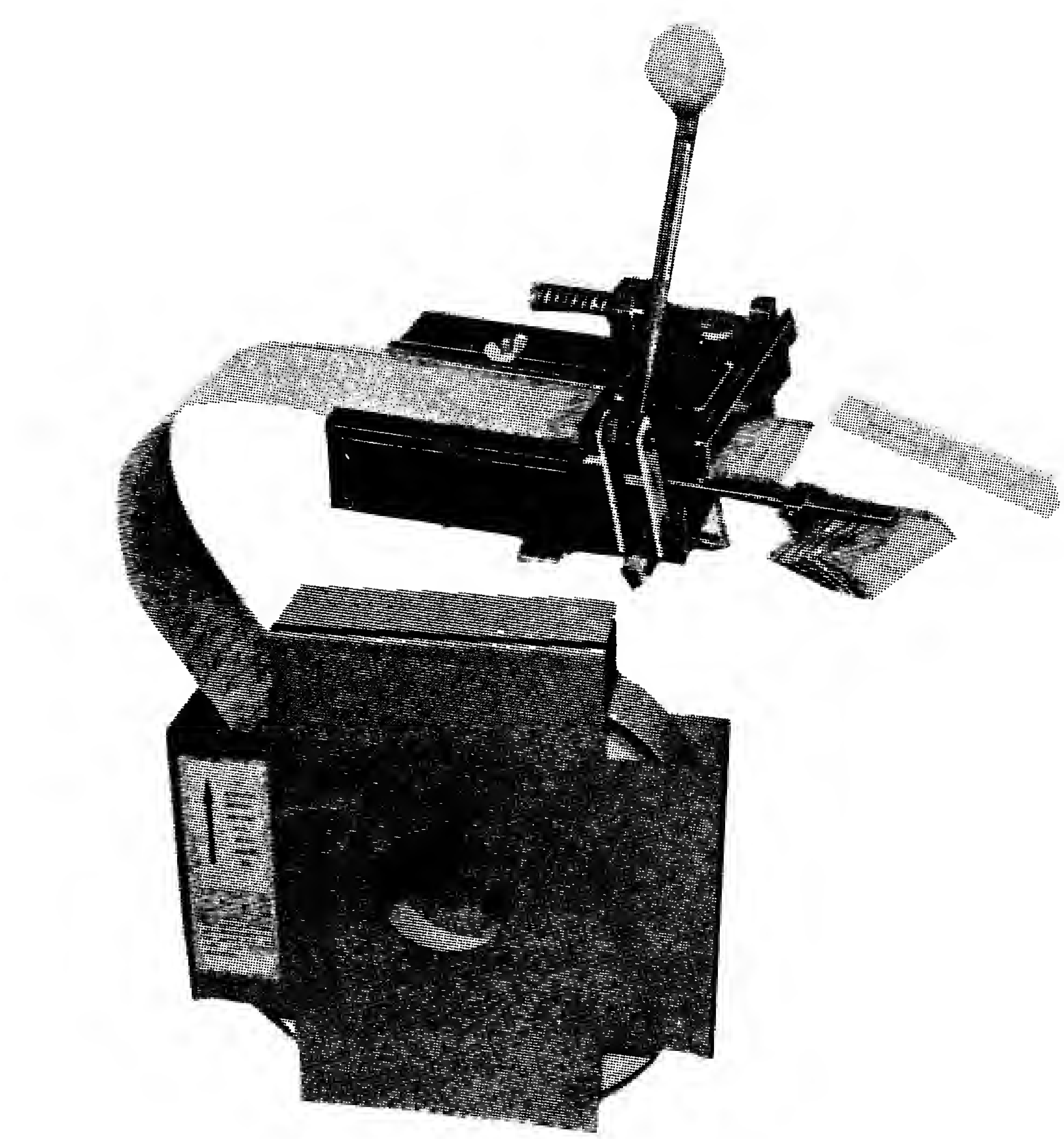


Fig. 1–84. One-step slot-liner former *(Lenni Products)*

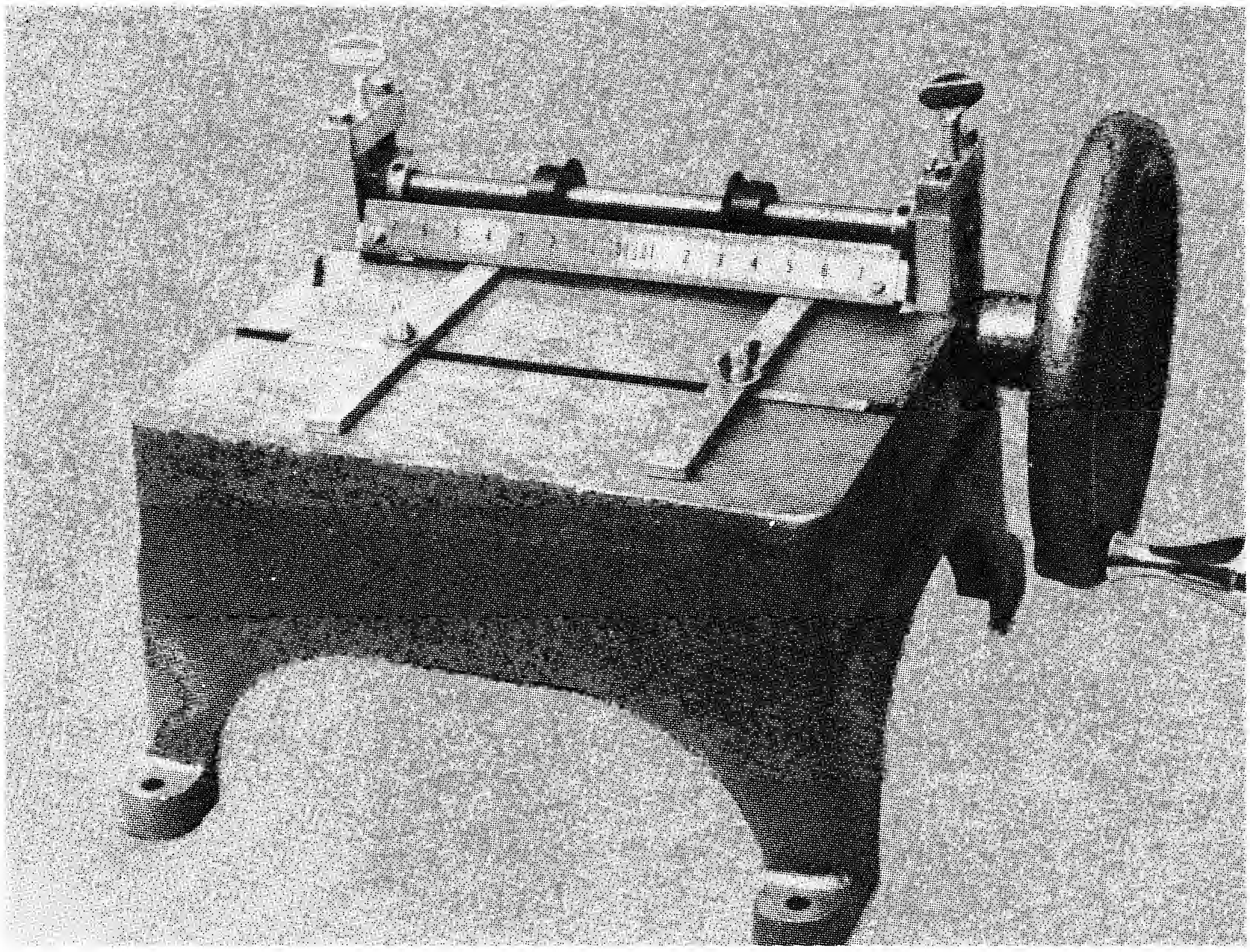


Fig. 1–85. Roller-type slot-liner former. *(Crown Industrial Products)*

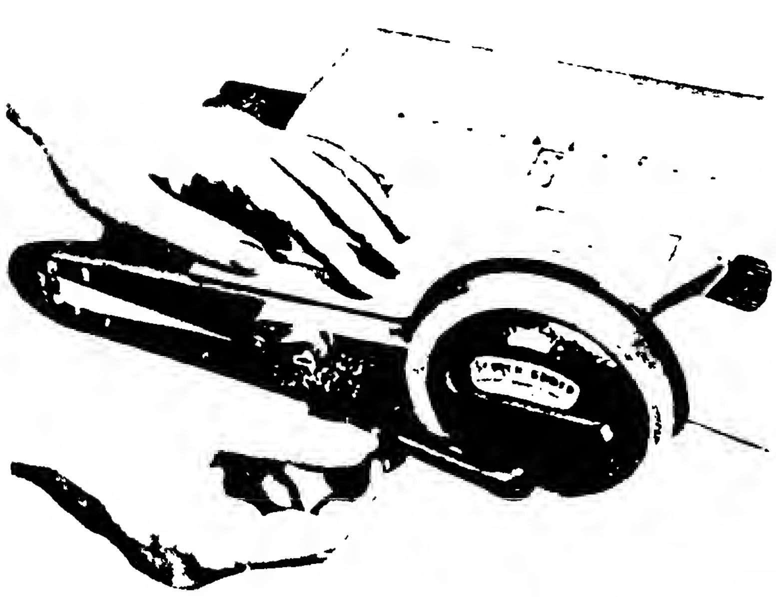


Fig. 1–86. Machine used to form reinforcing tape on the slot-liner insulation.

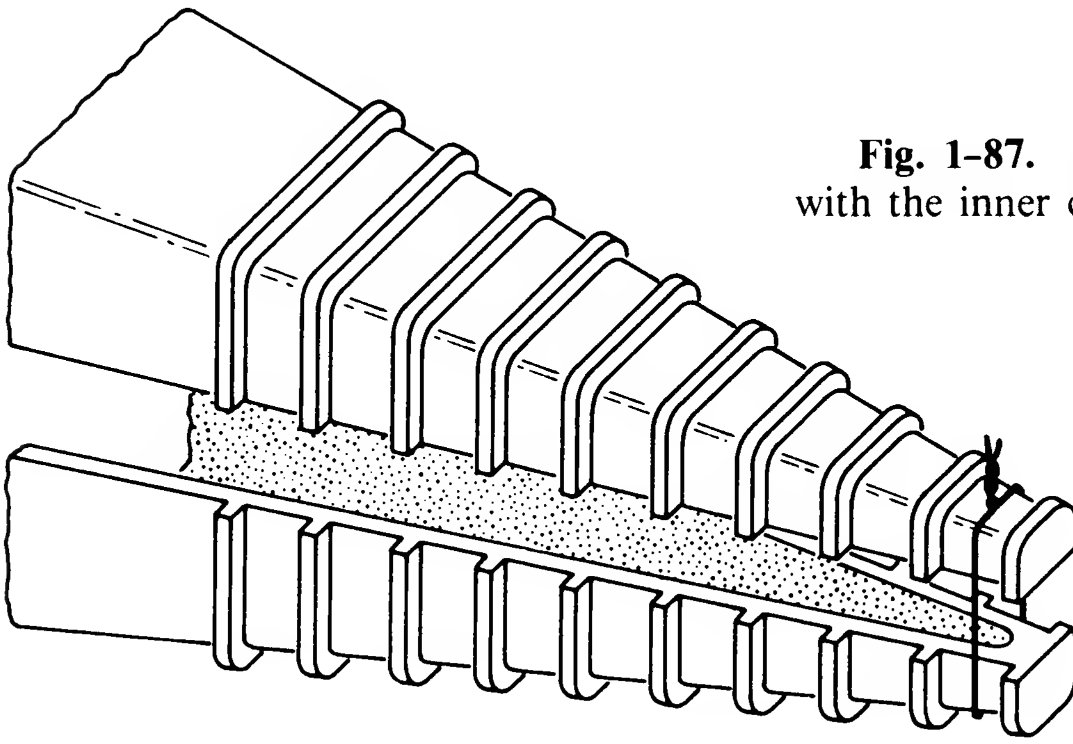


Fig. 1-87. Setting the winding head with the inner coil pattern.

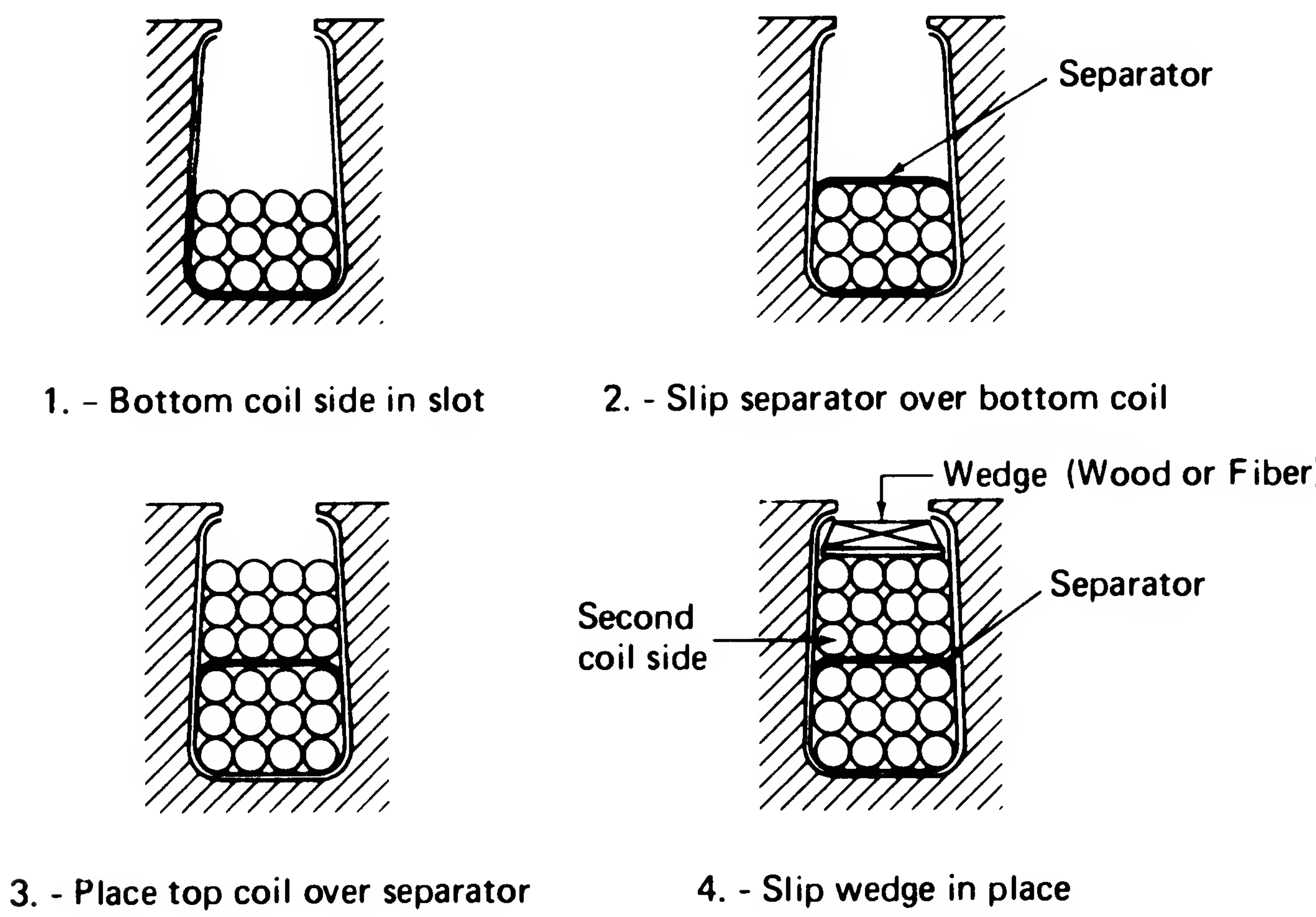


Fig. 1-88. Placement of slot separators and wedges.

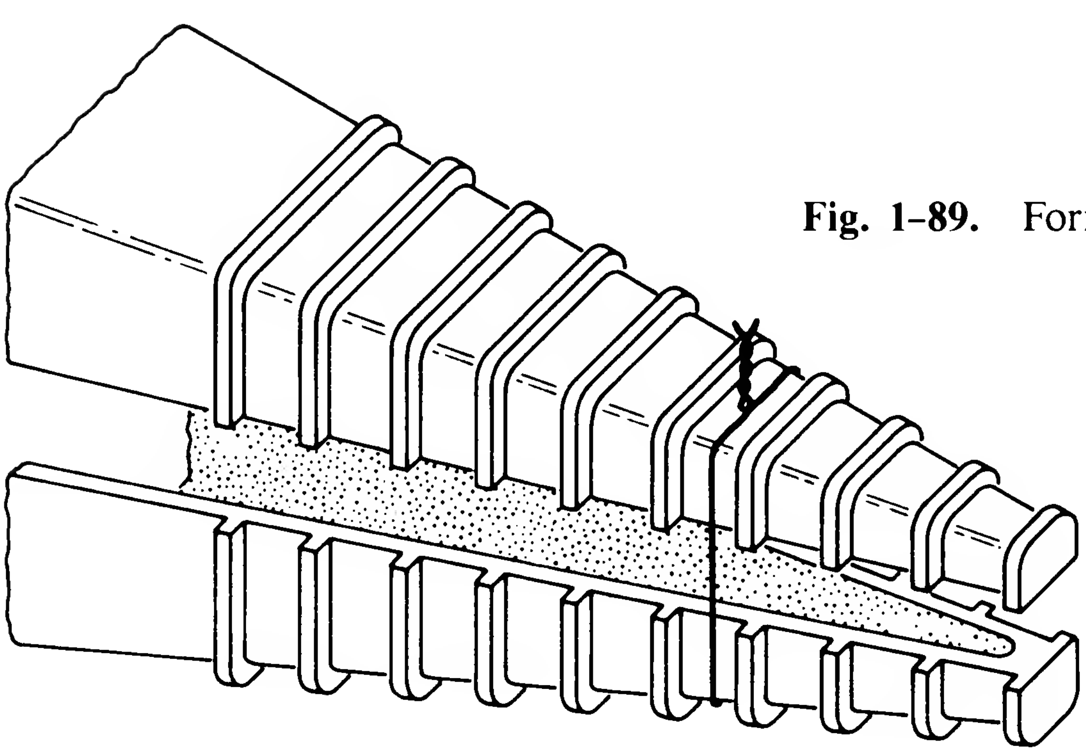


Fig. 1-89. Forming the second pattern.

Figures 1-87; 1-88; 1-89

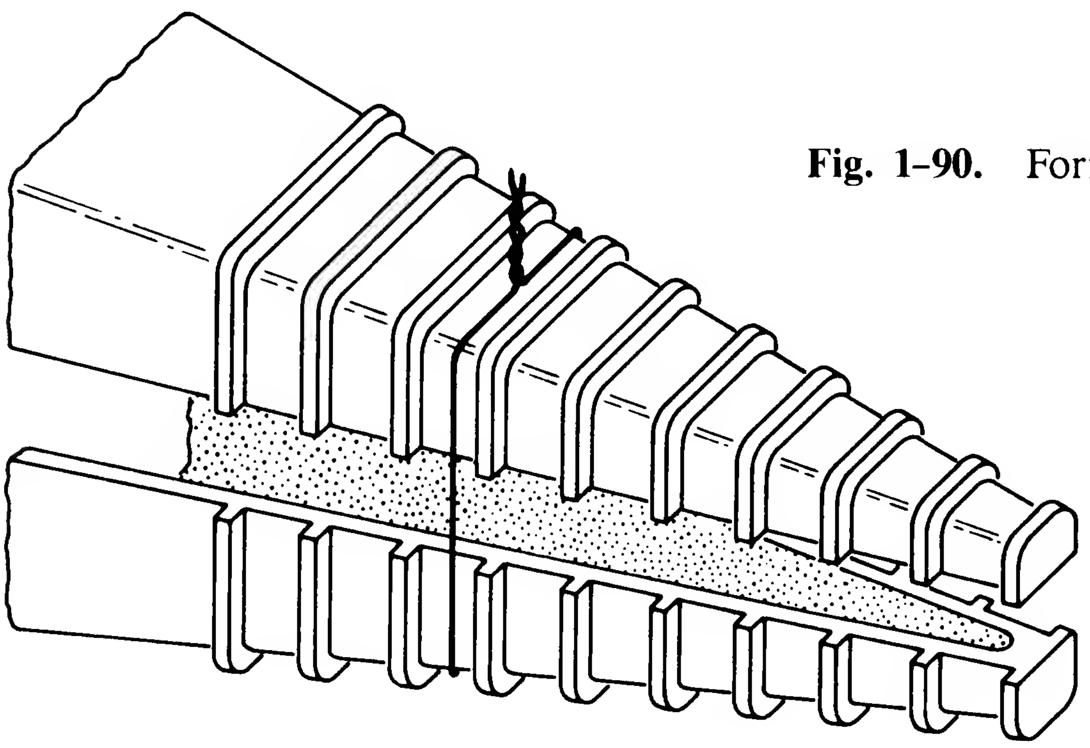


Fig. 1–90. Forming the third pattern.

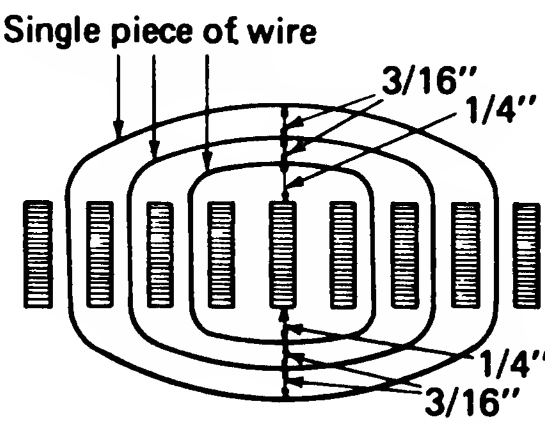


Fig. 1–91. A properly spaced pattern.

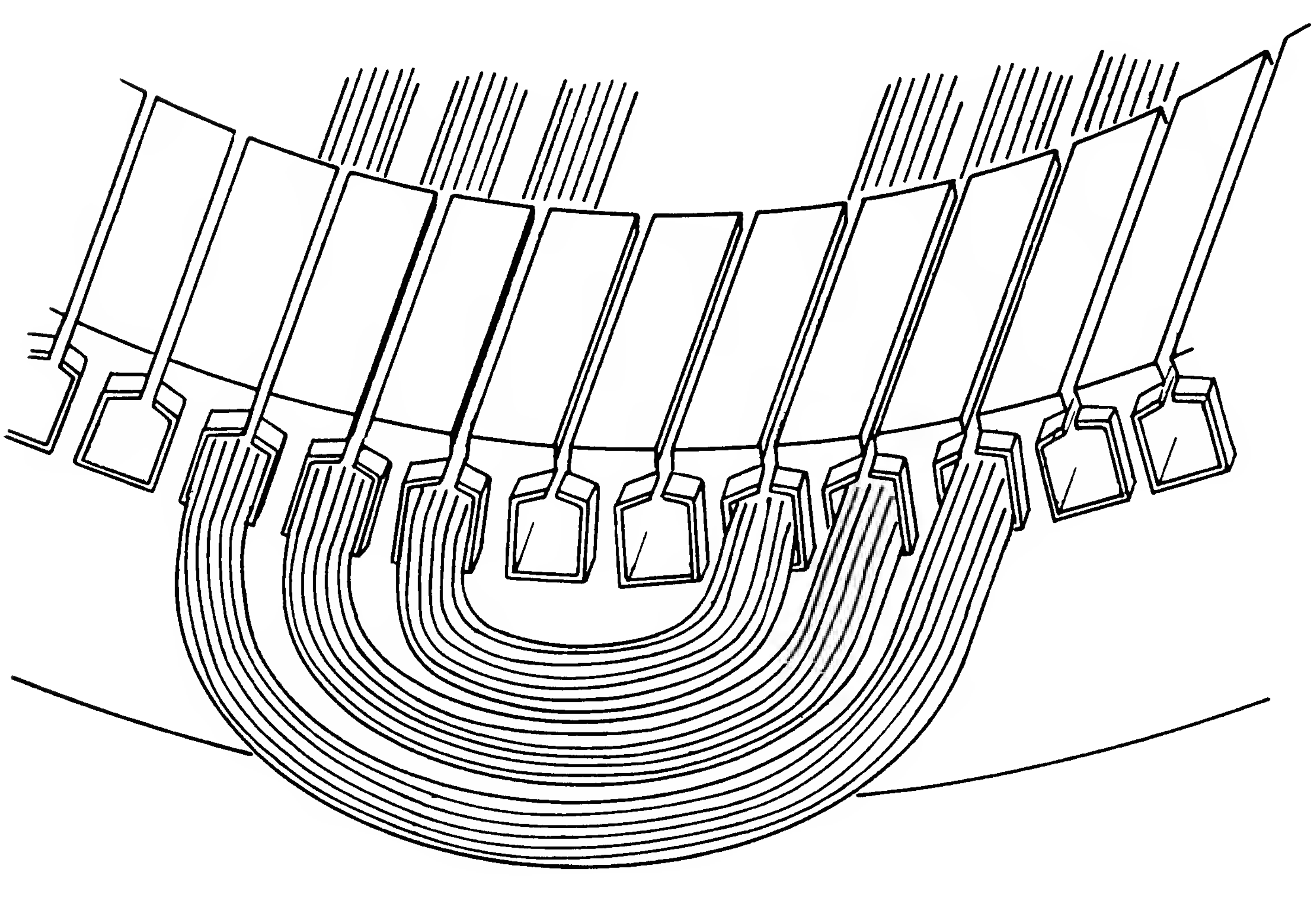


Fig. 1–92. A properly fitting coil will leave room to insert the start winding easily.

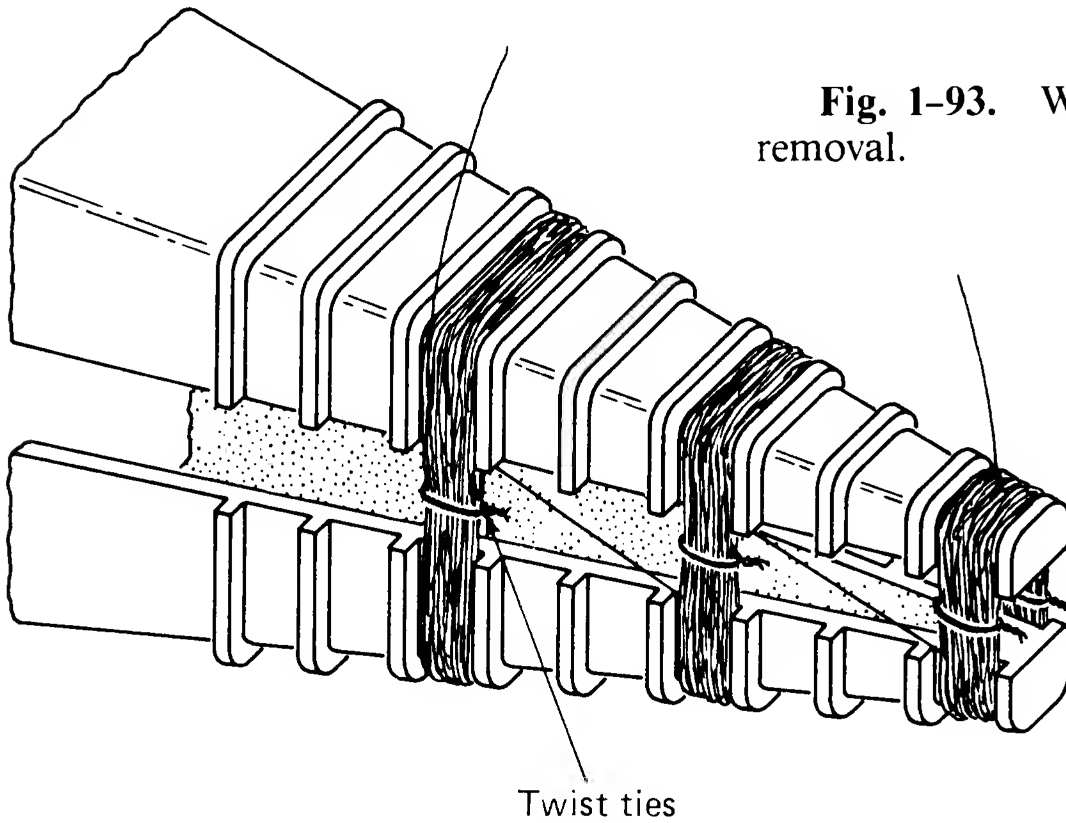


Fig. 1–93. Wound coil ready for removal.

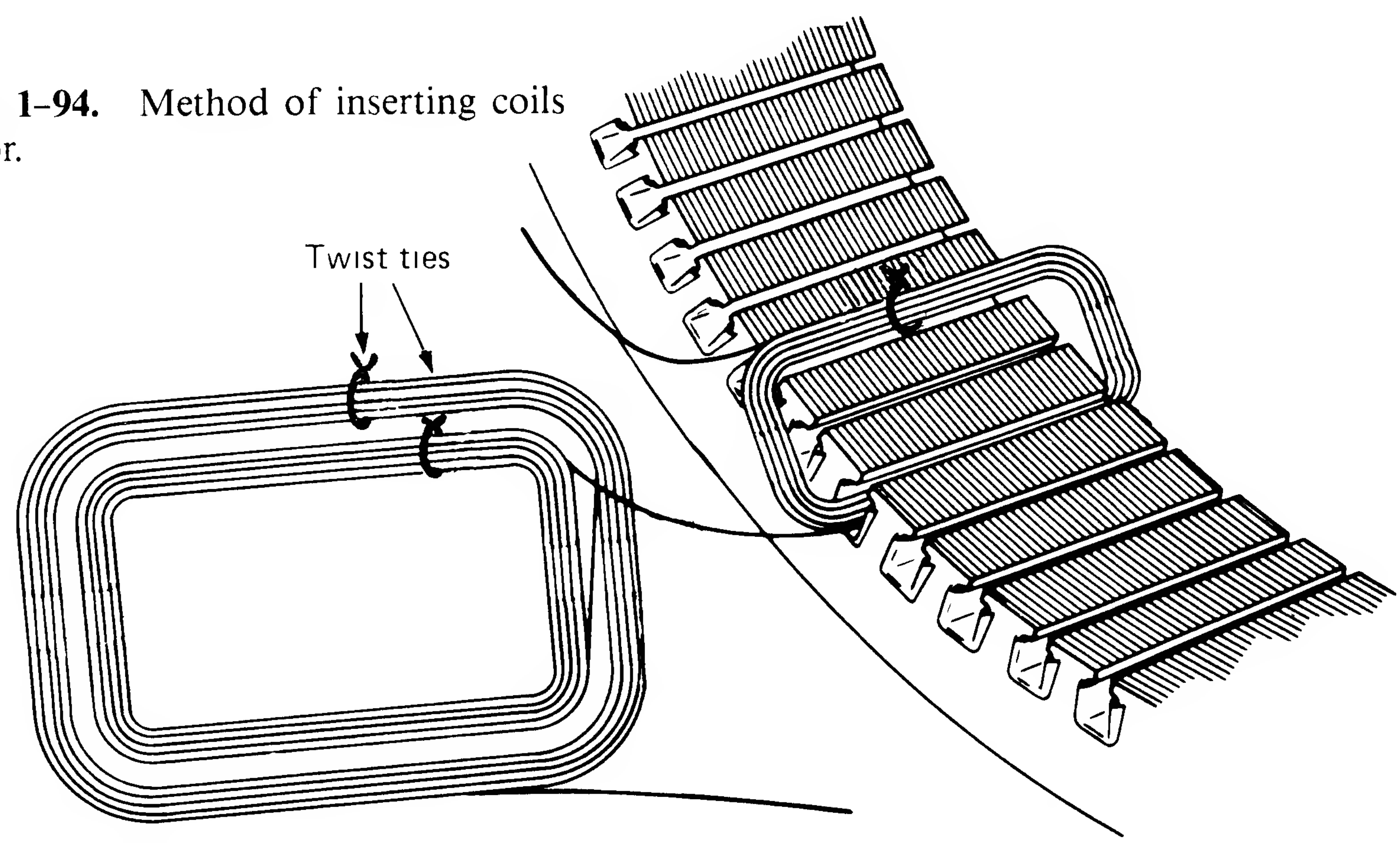


Fig. 1–94. Method of inserting coils in stator.

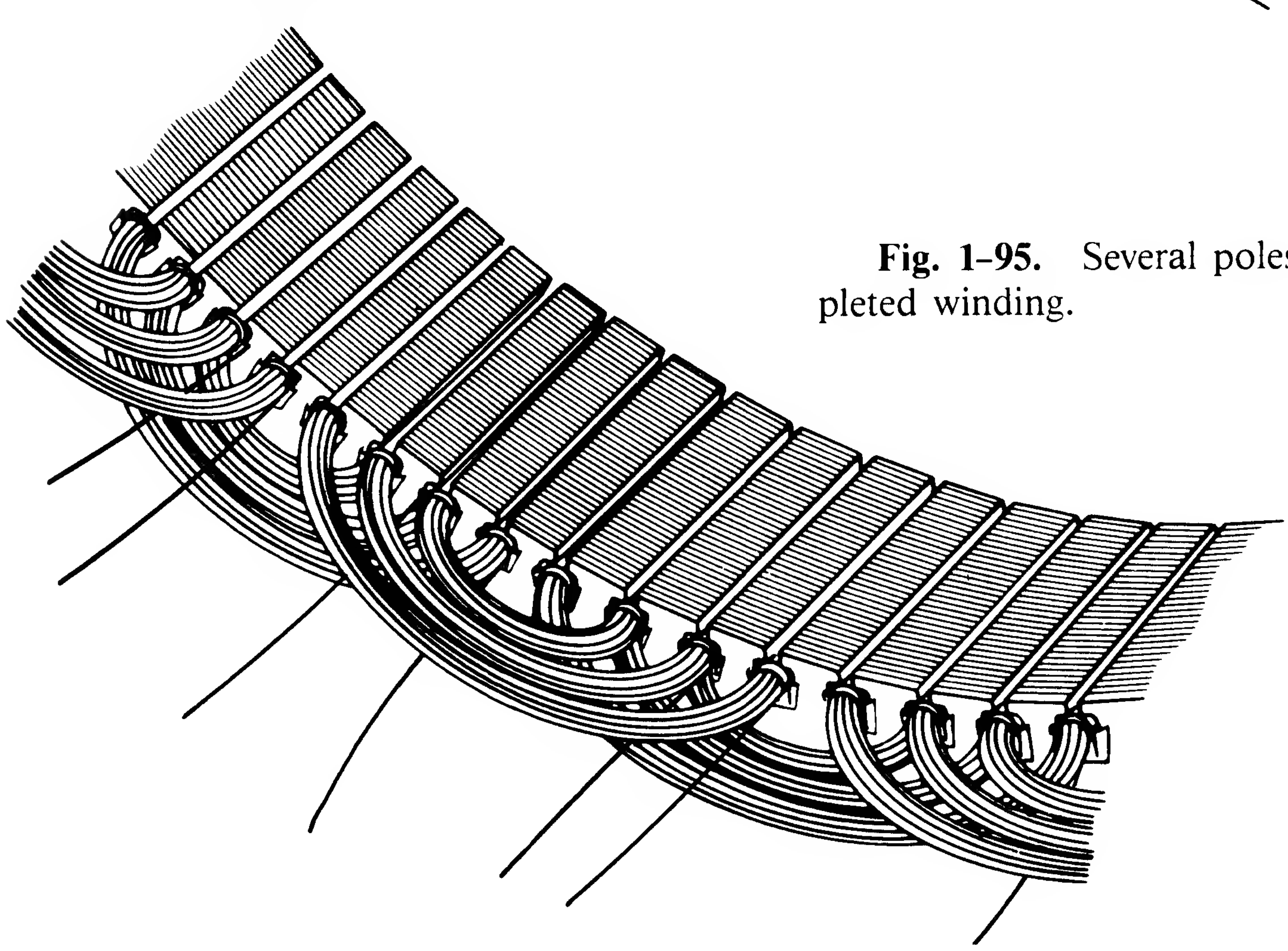


Fig. 1–95. Several poles of completed winding.

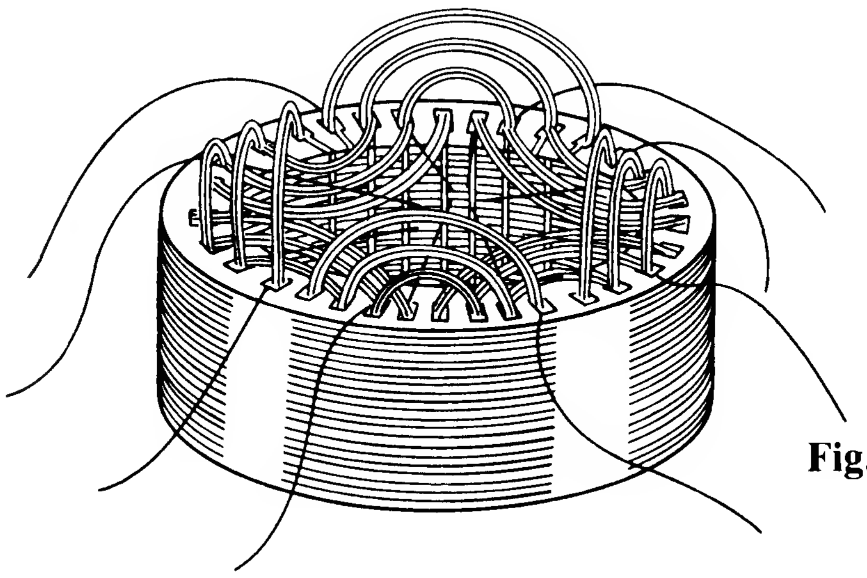


Fig. 1–96. Stator ready for connecting.

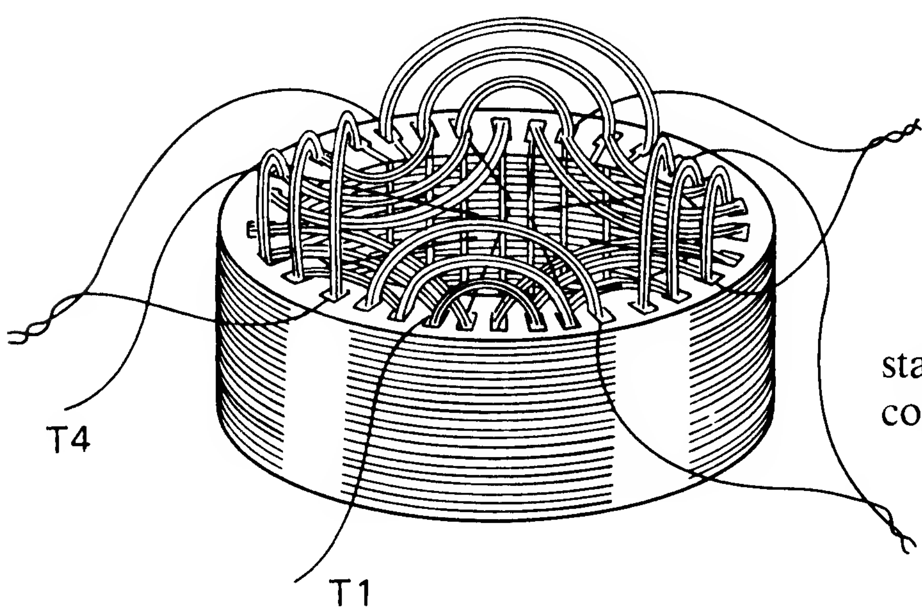


Fig. 1–97. Connecting procedure, starting at the bottom and proceeding counterclockwise.

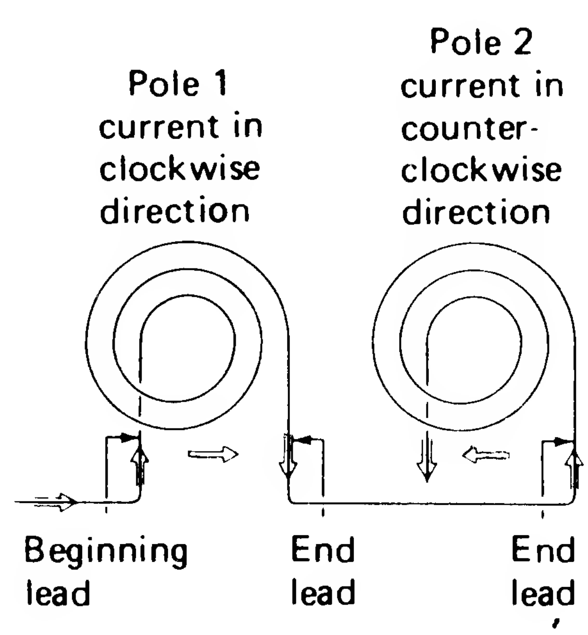


Fig. 1–98. The connection of adjacent poles to obtain opposite polarity.

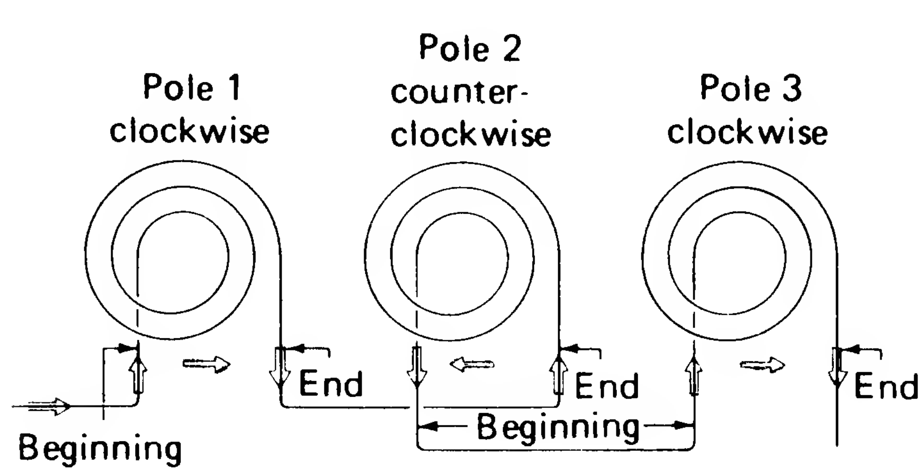


Fig. 1–99. The connections of three poles.

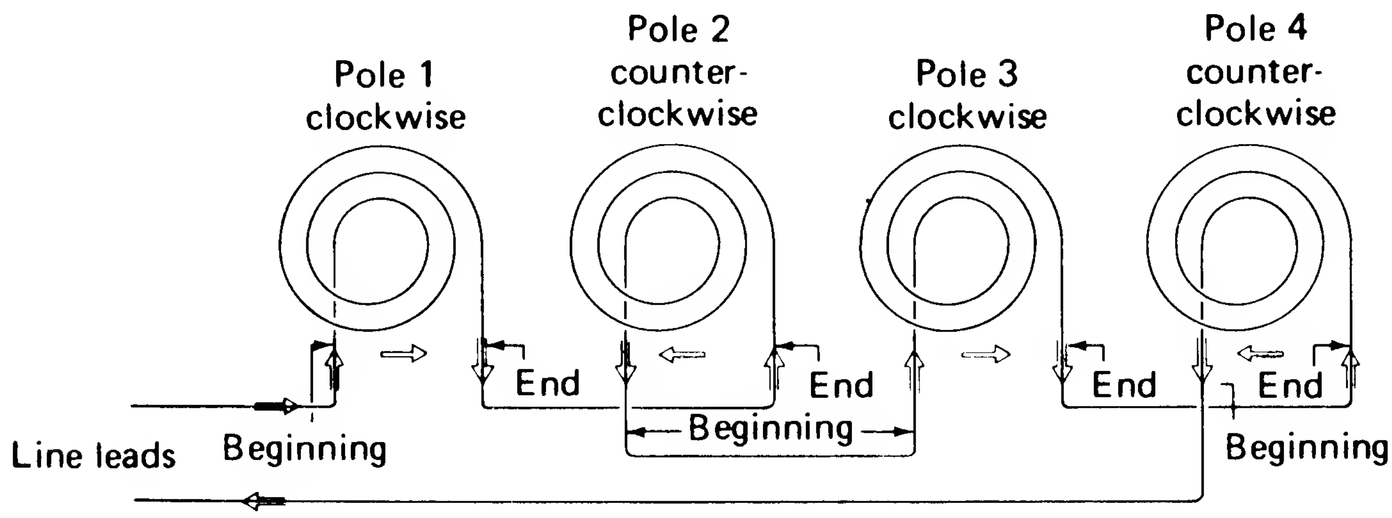


Fig. 1-100. Four poles connected together and to the line.

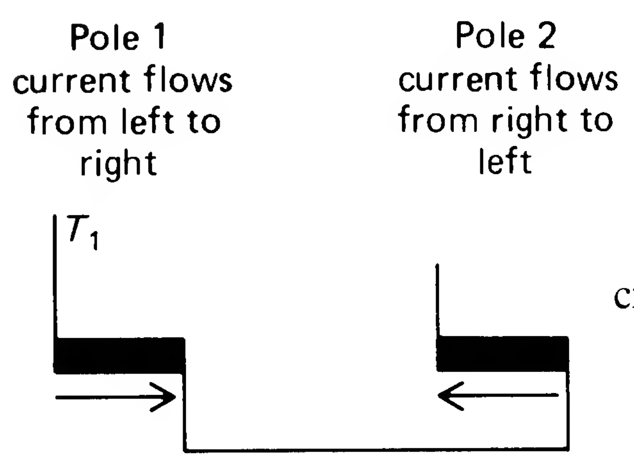
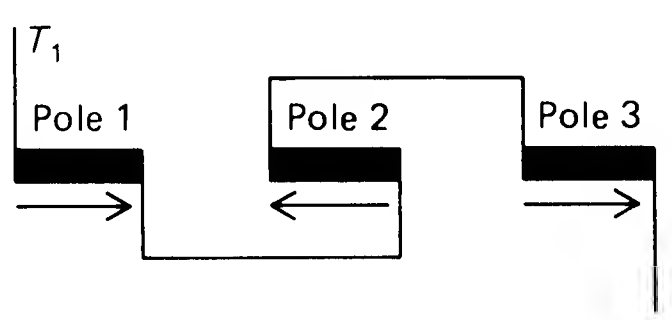


Fig. 1-101. A block diagram of the circuit in **Fig. 1-98.**

Fig. 1-102. (Continued from **Fig. 1-101**). The beginning or left of Pole 2 connects to the beginning or left of Pole 3.



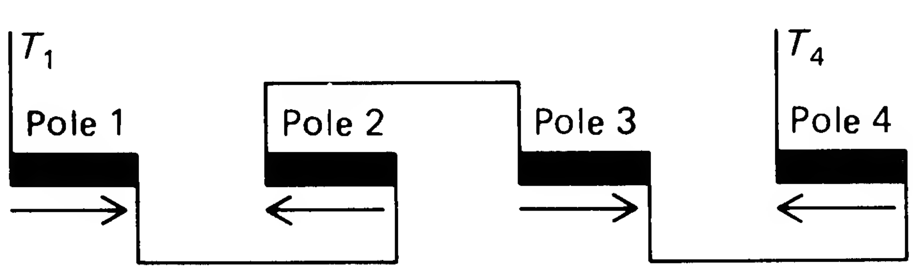


Fig. 1-103. The end or right of Pole 3 connects to the end or right of Pole 4. The line is connected to the beginning or left of Pole 1 (T_1) and the beginning or left of Pole 4 (T_4).

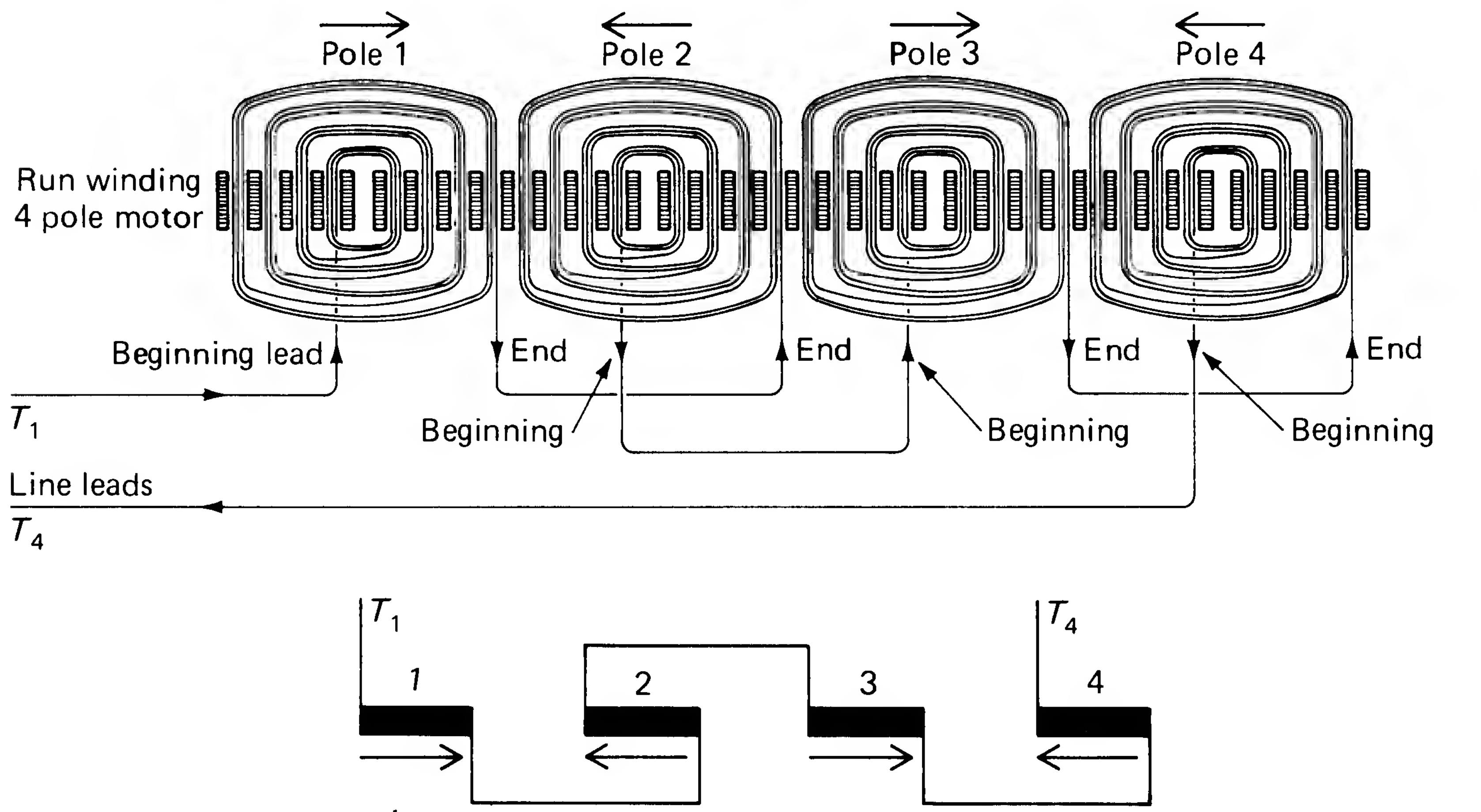


Fig. 1–104. Four poles of the run or main winding. The poles are connected so that the current through Pole 1 is from left to right in Pole 1, right to left in Pole 2, left to right in Pole 3, and right to left in Pole 4.

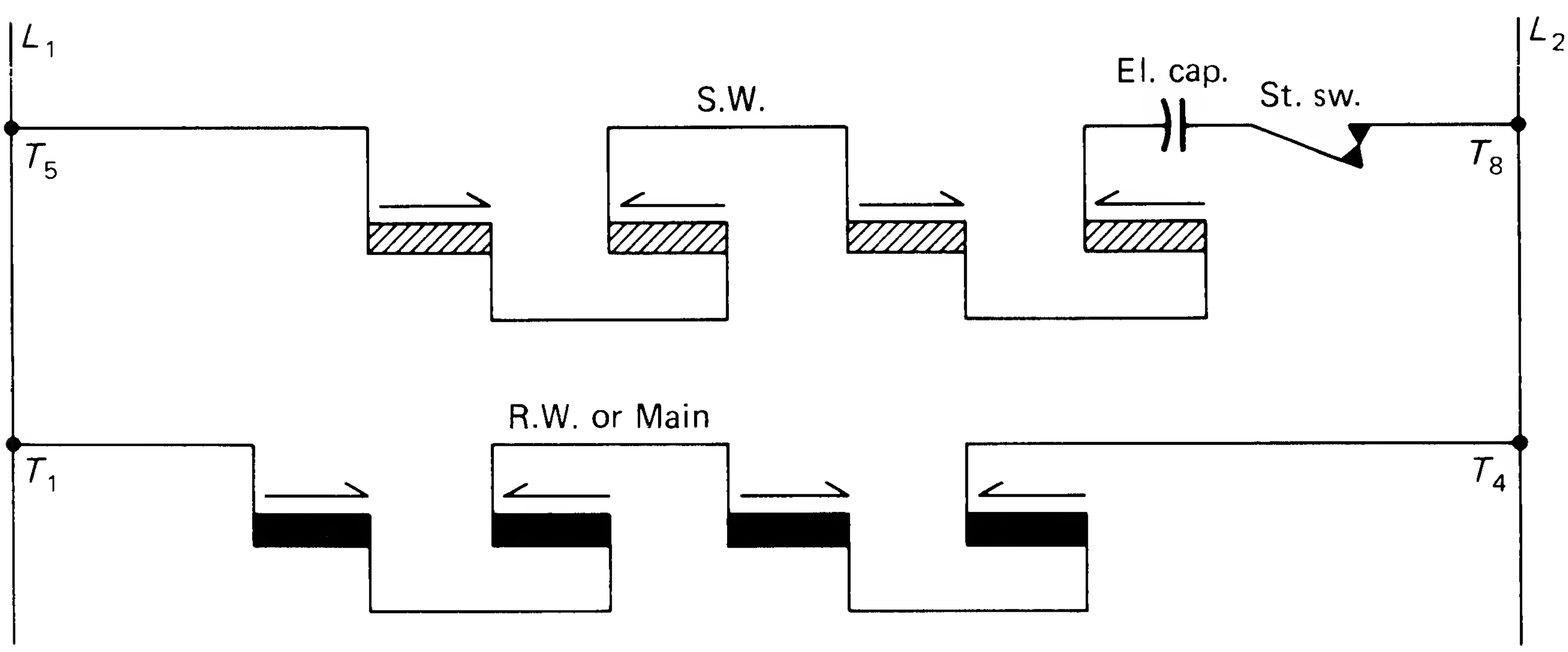


Fig. 1–105. A four-pole capacitor-start motor connection.

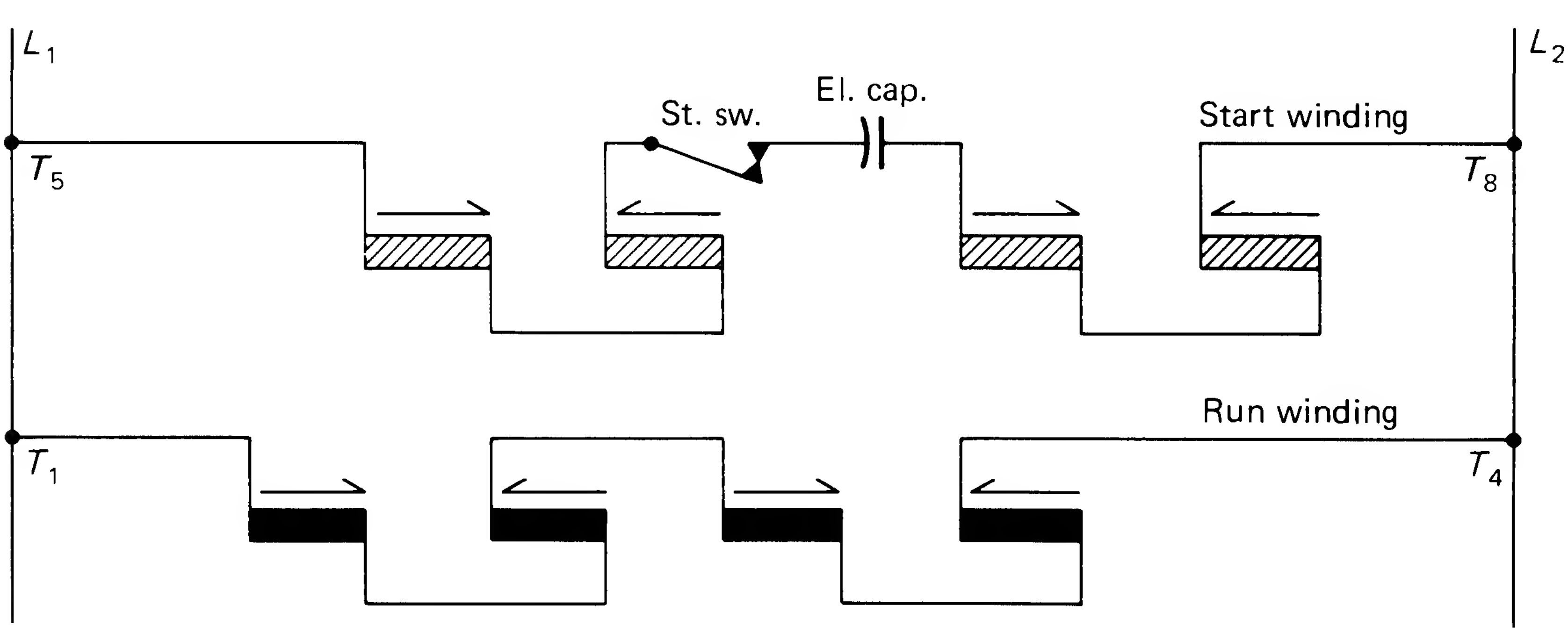


Fig. 1–106. A four-pole capacitor-start motor showing the stationary switch and capacitor connected in the center of the start winding.

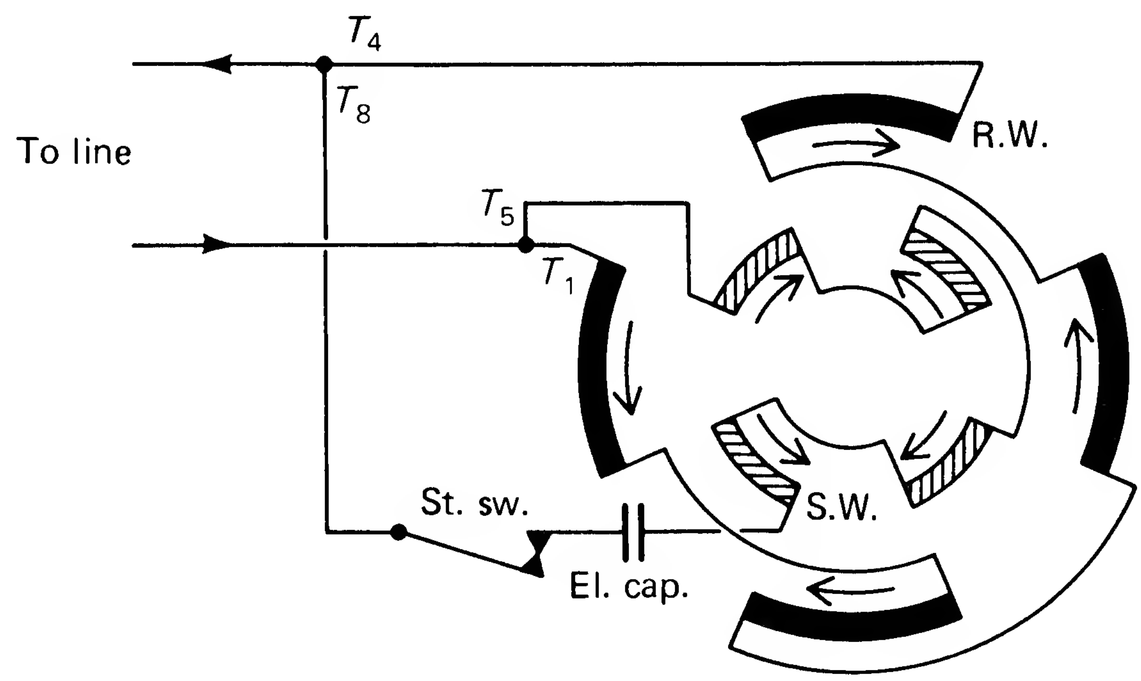


Fig. 1–107. A four-pole capacitor-start motor connection shown in a circular diagram.

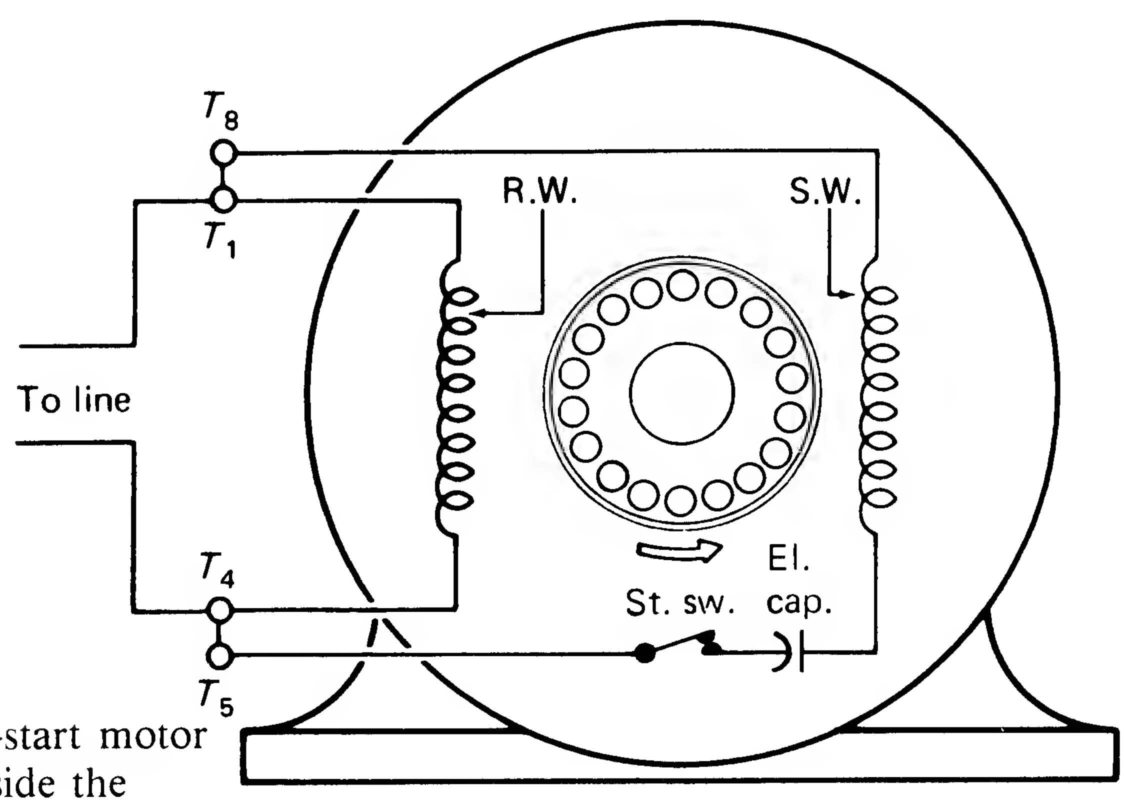


Fig. 1–108. A capacitor-start motor with four leads brought outside the frame for reversing.

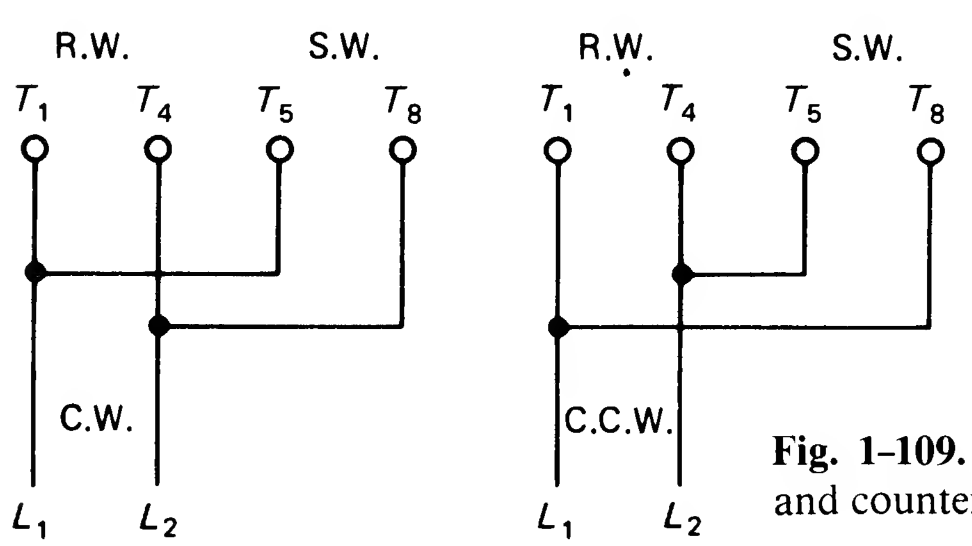


Fig. 1–109. Terminal connection for clockwise and counterclockwise rotation.

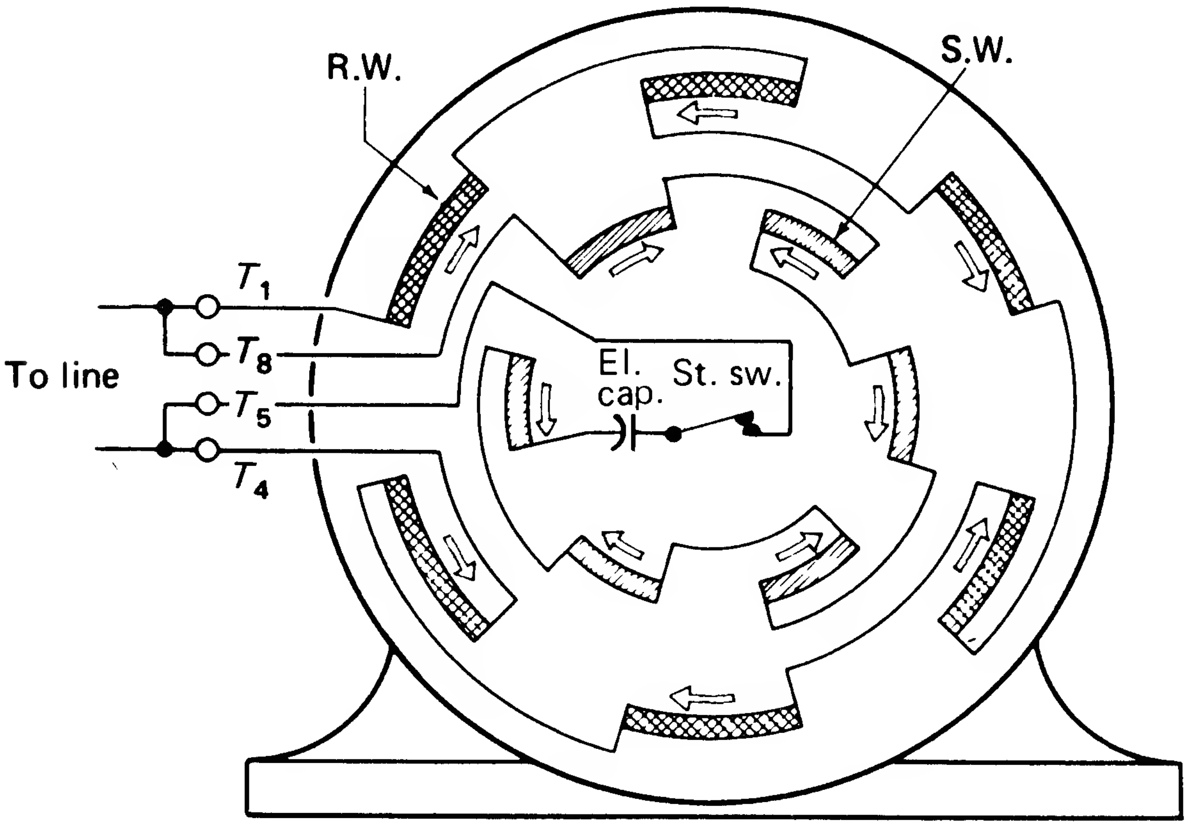


Fig. 1-110. The connections of a six-pole, capacitor-start motor.

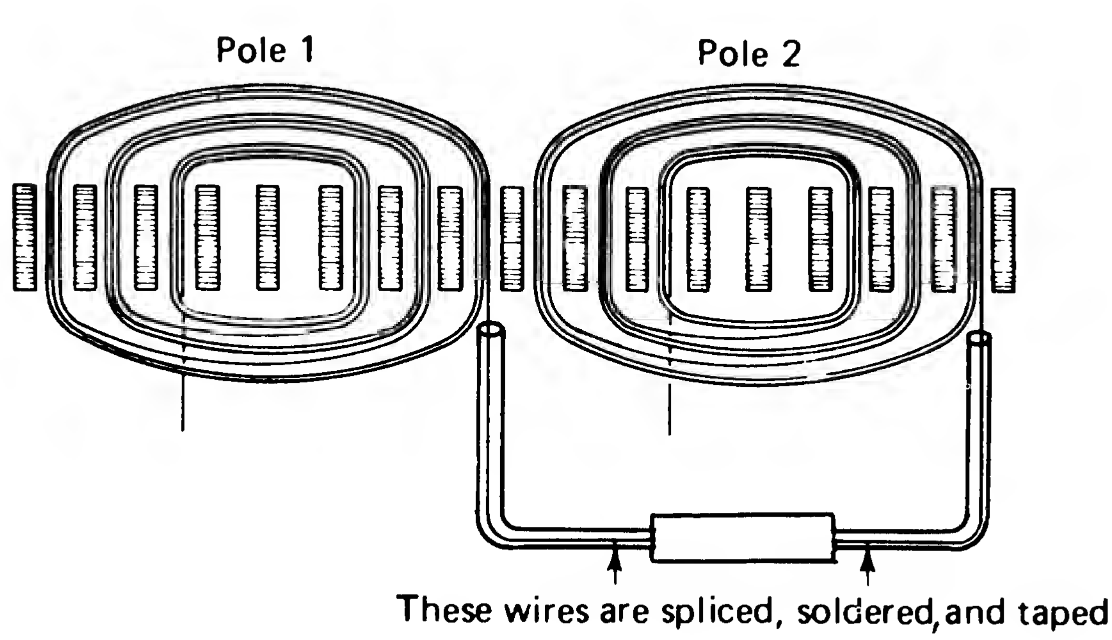


Fig. 1-111. One method of connecting wires between poles.

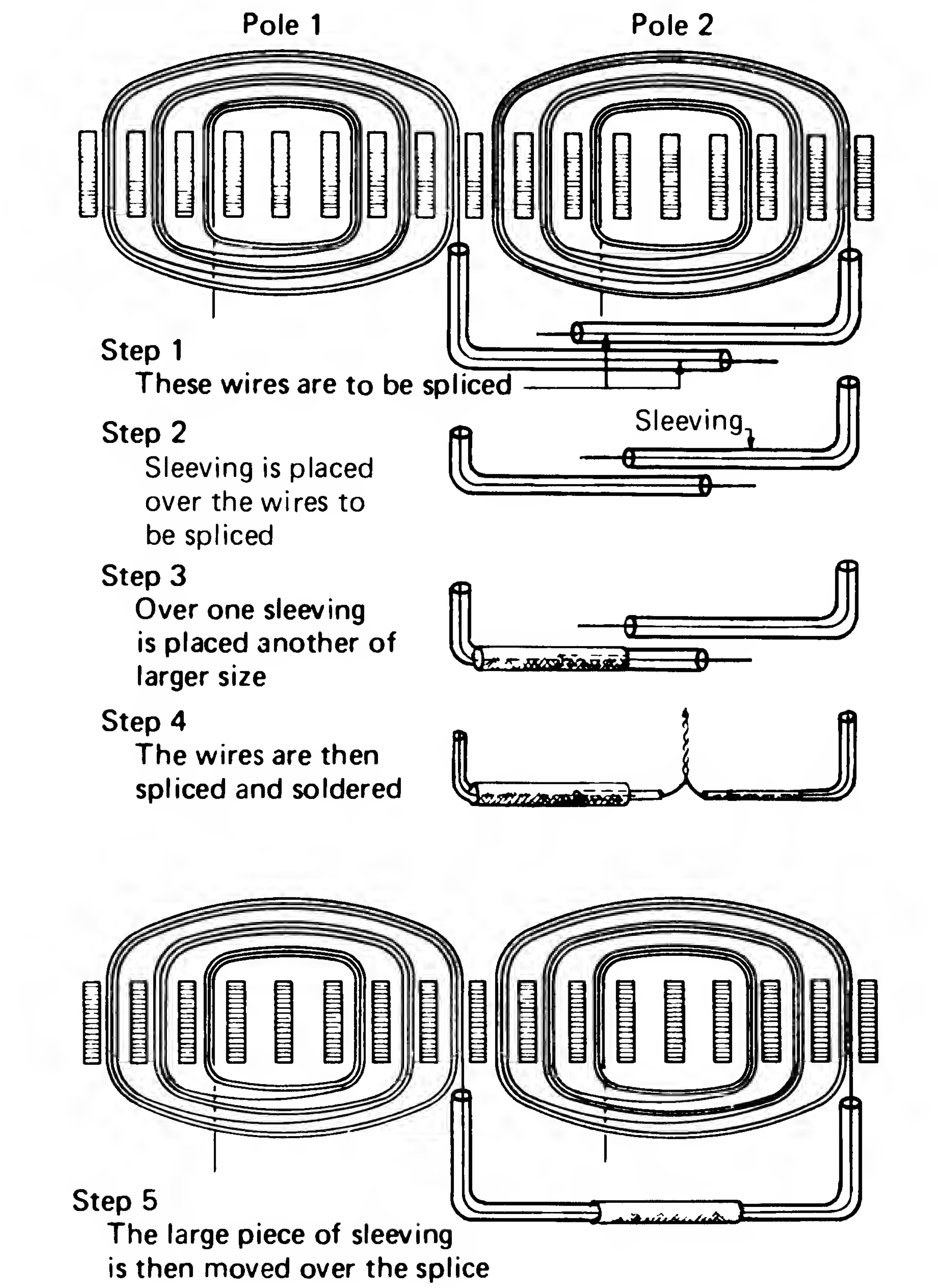


Fig. 1-112a. A method of connecting leads together.

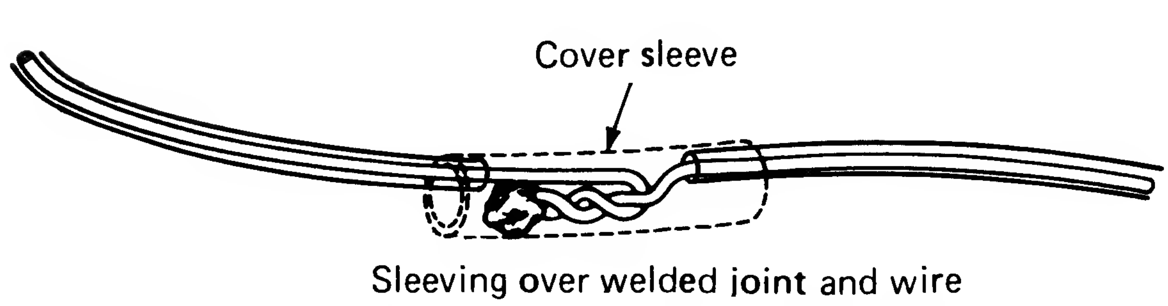


Fig. 1-112b. Welded joint with sleeving of insulation.

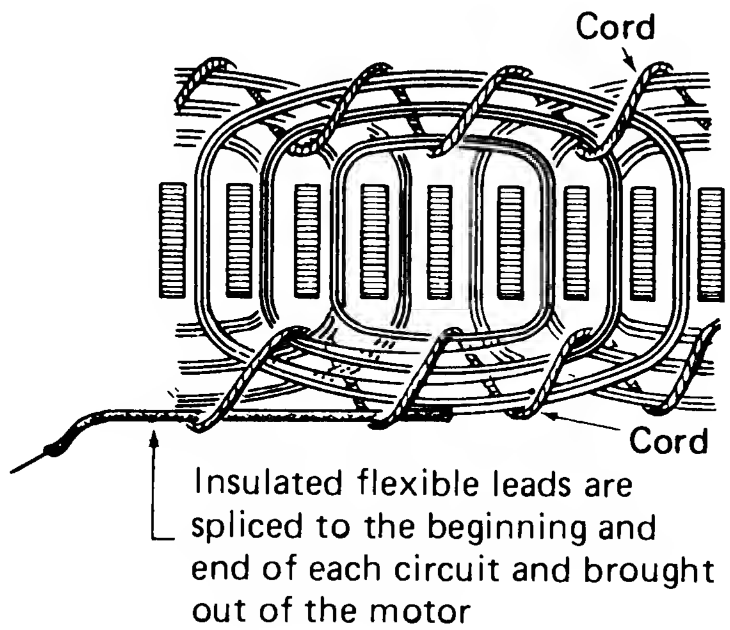


Fig. 1-113. The lead is tied to the winding with cord so that it cannot be broken off. The windings are also tied to one another to prevent vibration of the wires.

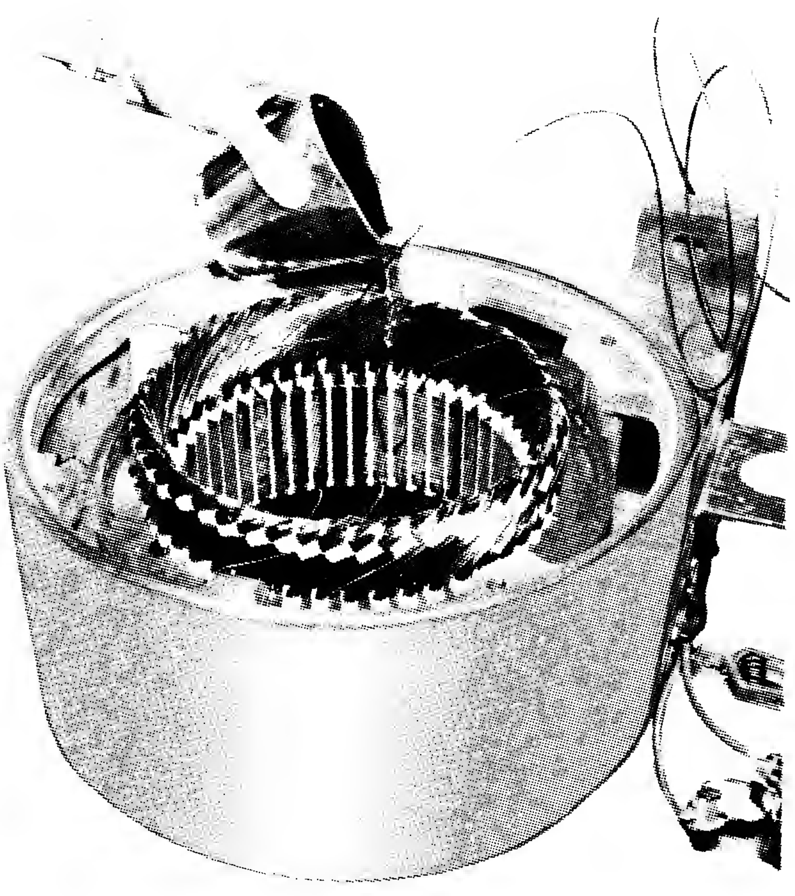


Fig. 1-114. Manual application of solventless resin. *(3M Company)*

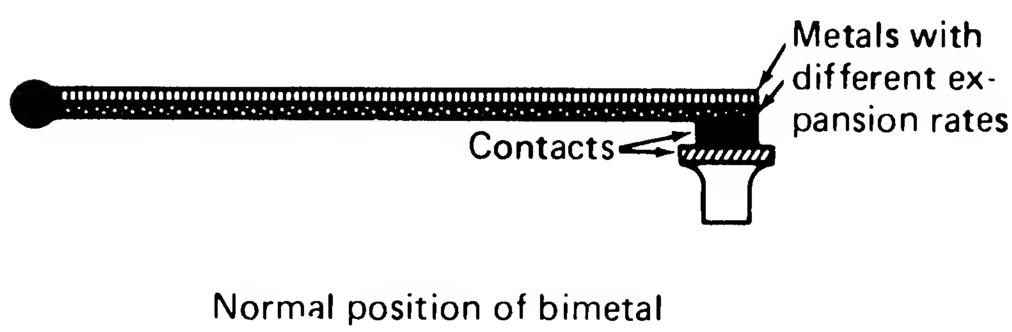


Fig. 1-115. Bimetal overload protector.

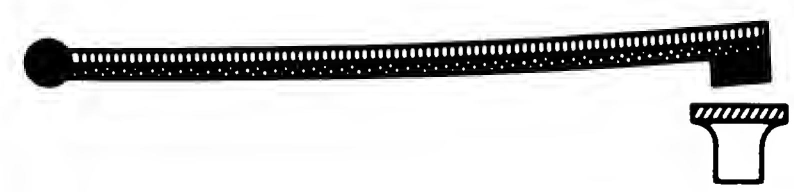


Fig. 1-116. Bimetal overload protector.

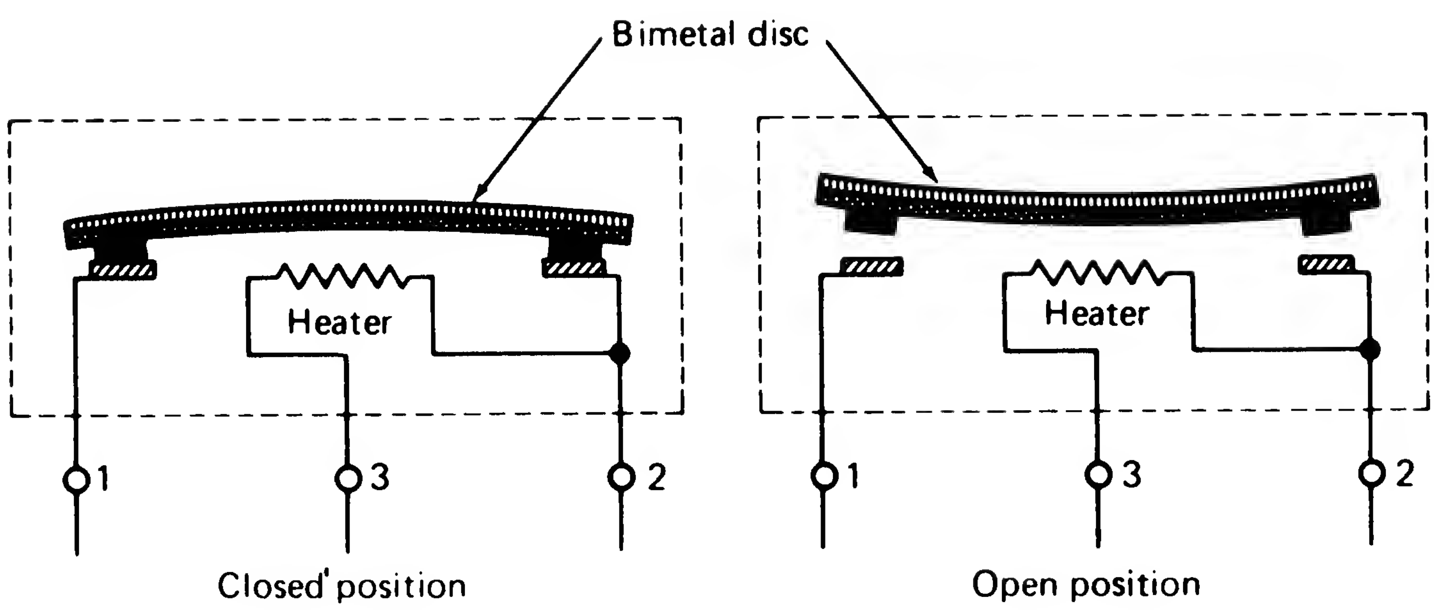


Fig. 1-117. Three-terminal overload protector with heater.

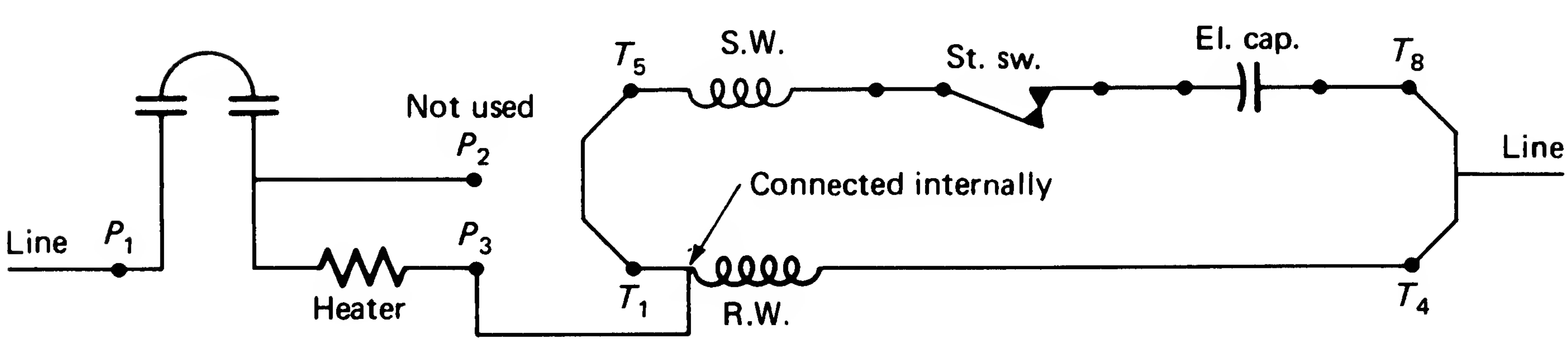
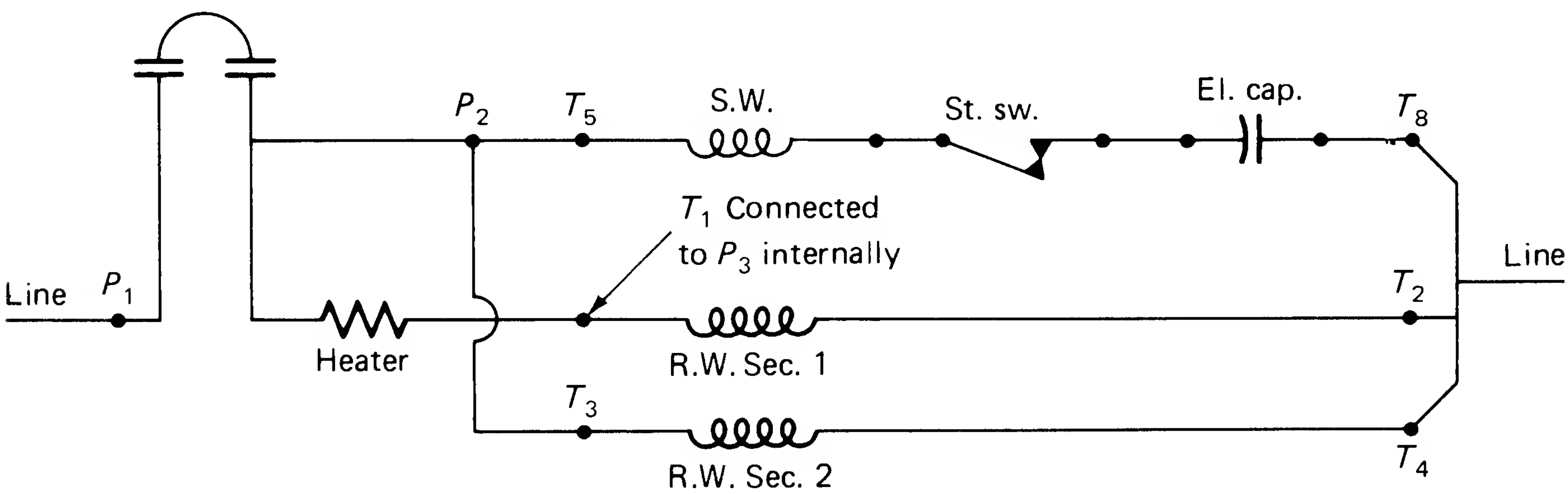
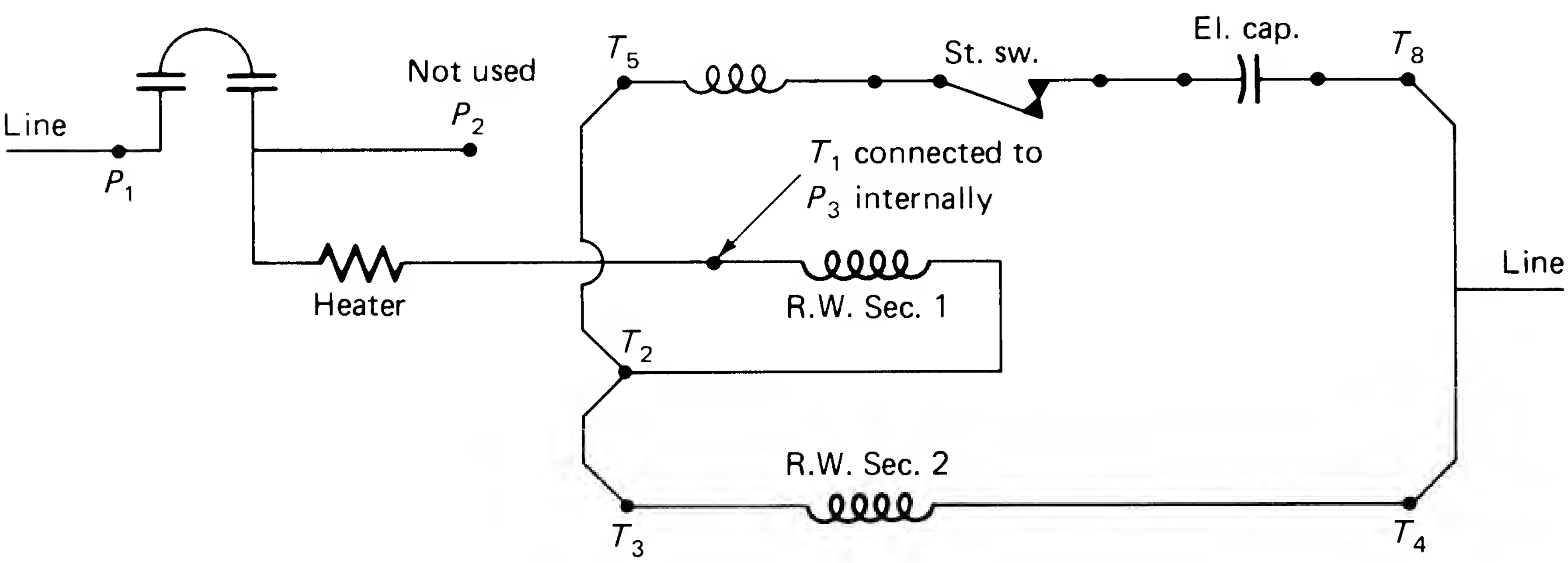


Fig. 1-118. A single-voltage motor with P_3 connected internally to T_1. T_1 is accessible to T_4, T_5, T_8, and P_1.



a) Low-voltage connection



b) High-voltage connection

Fig. 1-119. Dual-voltage motor showing (a) the low-voltage connection and (b) the high-voltage connection. T_1 is connected to P_3 internally. All leads except T_1 and P_3 are accessible.

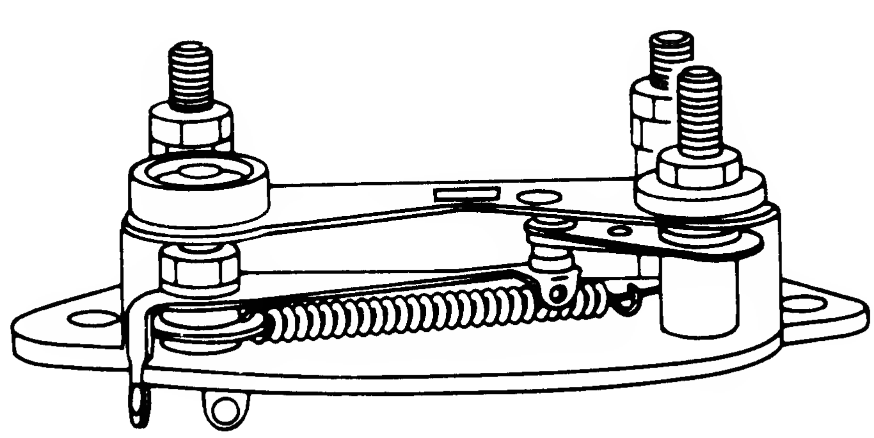


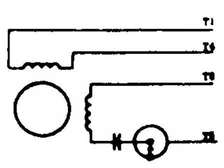
Fig. 1-120. Bimetal type thermotron *(Delcro Products).*

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

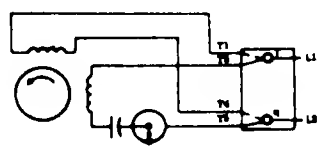
Single Voltage—Without Thermal Protector

Line Leads

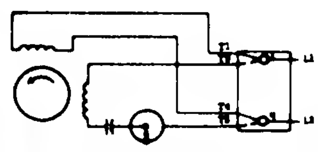


	L1	L2
Counter-clockwise rotation	T1, T8	T4, T5
Clockwise rotation	T1, T5	T4, T8

Terminal Board



To obtain clockwise rotation, interchange leads T5 and T8

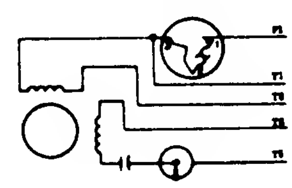


To obtain clockwise rotation interchange leads T1 and T4

NOTE—When terminal boards are shown they are viewed from the front. Dotted lines indicate permanent connection

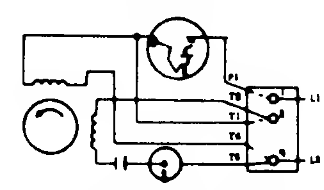
Single Voltage—With Thermal Protector

Line Leads

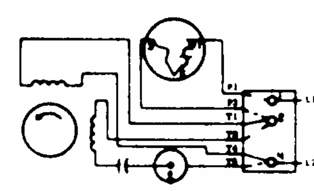


	L1	L2	Join
Counter-clockwise rotation	P1	T4, T5	T1, T8
Clockwise rotation	P1	T4, T8	T1, T5

Terminal Board



To obtain clockwise rotation, interchange leads T5 and T8



To obtain clockwise rotation interchange leads T1 and T4

NOTE—When terminal boards are shown they are viewed from the front. Dotted lines indicate permanent connection

TERMINAL MARKINGS

Fig. 1-121a. Schematic diagrams for capacitor-start motors—reversible.

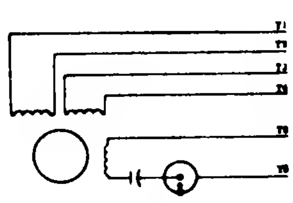
MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—*(Continued)*

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

TERMINAL MARKINGS

Double Voltage—Without Thermal Protector

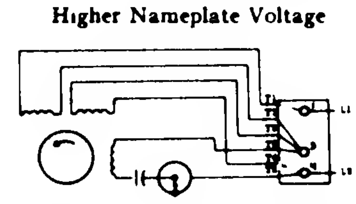
Line Leads



		L1	L2	Join
Higher name-plate voltage	Counter clockwise rotation	T1	T4, T5	T2, T3 and T8
	Clockwise rotation	T1	T4, T8	T2, T3 and T5
Lower name-plate voltage	Counter-clockwise rotation	T1, T3 T8	T2, T4, T5	
	Clockwise rotation	T1 T3 T5	T2 T4 T8	

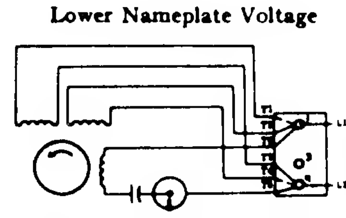
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8

Lower Nameplate Voltage

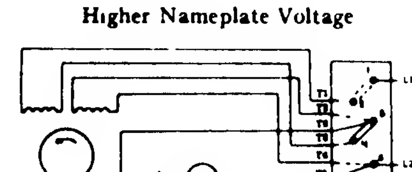


To obtain clockwise rotation interchange leads T5 and T8

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection

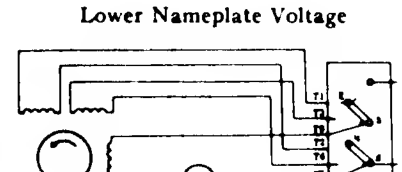
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation interchange leads T5 and T8

Lower Nameplate Voltage



To obtain clockwise rotation interchange leads T5 and T8

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection

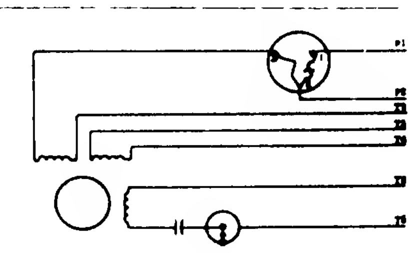
Fig. 1-121b. Schematic diagrams for capacitor-start motors—reversible (*continued*).

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—(*Continued*)

NOTE I—The design proportions for dual-voltage, reversible, capacitor start motors are such that three different groups of diagrams are necessary to show the means for obtaining adequate protection for these motors. These three groups of diagrams (I, II, and III) insert the thermal protector at different points in the circuit, therefore, different currents are provided to actuate the thermal protector.
NOTE II—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

GROUP I—DOUBLE VOLTAGE—WITH THERMAL PROTECTOR

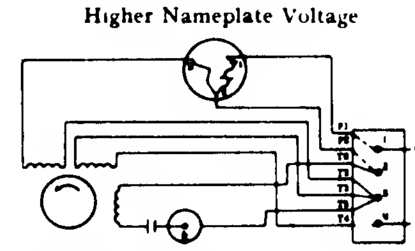
Line Leads



		L1	L2	Join	Join
Higher nameplate voltage	Counter-clockwise rotation	P1	T4	P2, T8	T2 T3 T5
	Clockwise rotation	P1	T4	P2, T5	T2 T3, T8
Lower nameplate voltage	Counter-clockwise rotation	P1	T2 T4 T5	P2 T3 T8	
	Clockwise rotation	P1	T2 T4 T8	P2 T3 T5	

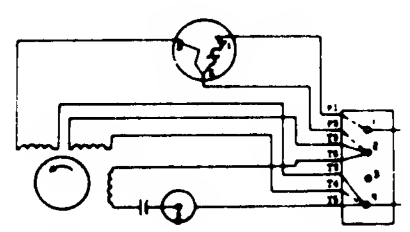
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation interchange leads T5 and T8

Lower Nameplate Voltage

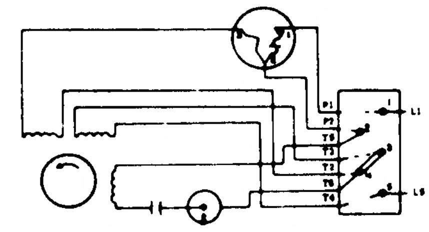


To obtain clockwise rotation interchange leads T5 and T8

NOTE III—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.
NOTE IV—Proper connection depends upon design of motor and thermal protector, refer to motor manufacturers information for proper diagram.

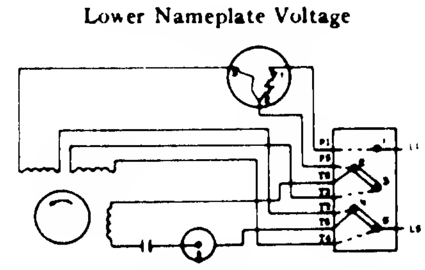
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation interchange leads T5 and T8

Lower Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

TERMINAL MARKINGS

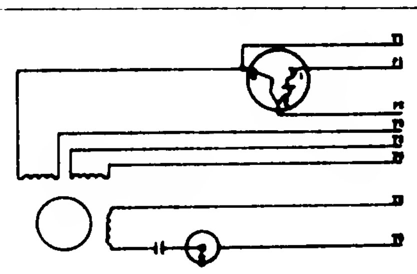
Fig. 1-121c. Schematic diagram for capacitor-start motors—reversible *(continued)*

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—(*Continued*)

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

GROUP II—DOUBLE VOLTAGE—WITH THERMAL PROTECTOR

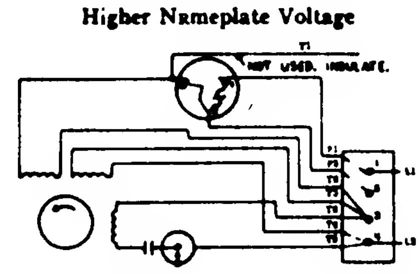
Line Leads



		L1	L2	Join	Join	Insulate Separately
Higher nameplate voltage	Counter-clockwise rotation	P1	T4, T5	T2, T3, T8		P2, T1
	Clockwise rotation	P1	T4, T8	T2, T3, T5		P2 T1
Lower nameplate voltage	Counter-clockwise rotation	P1	T2, T4, T5	P2, T3	T1, T8	
	Clockwise rotation	P1	T2 T4 T8	P2, T3	T1, T5	

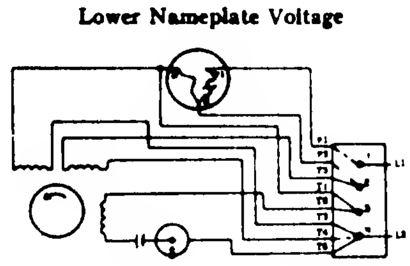
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation interchange leads T5 and T8

Lower Nameplate Voltage

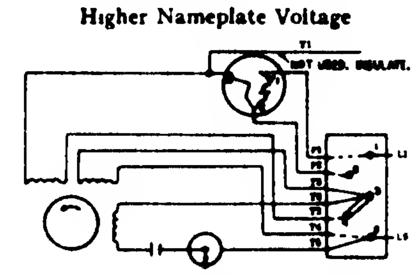


To obtain clockwise rotation, interchange leads T5 and T8

NOTE I—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.
NOTE II—Proper connection depends upon design of motor and thermal protector, refer to motor manufacturers information for proper diagram.

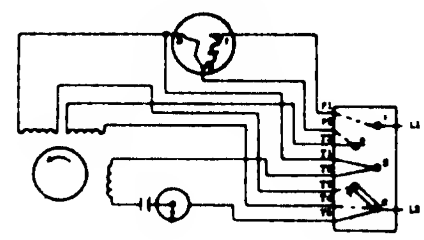
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8

Lower Nameplate Voltage

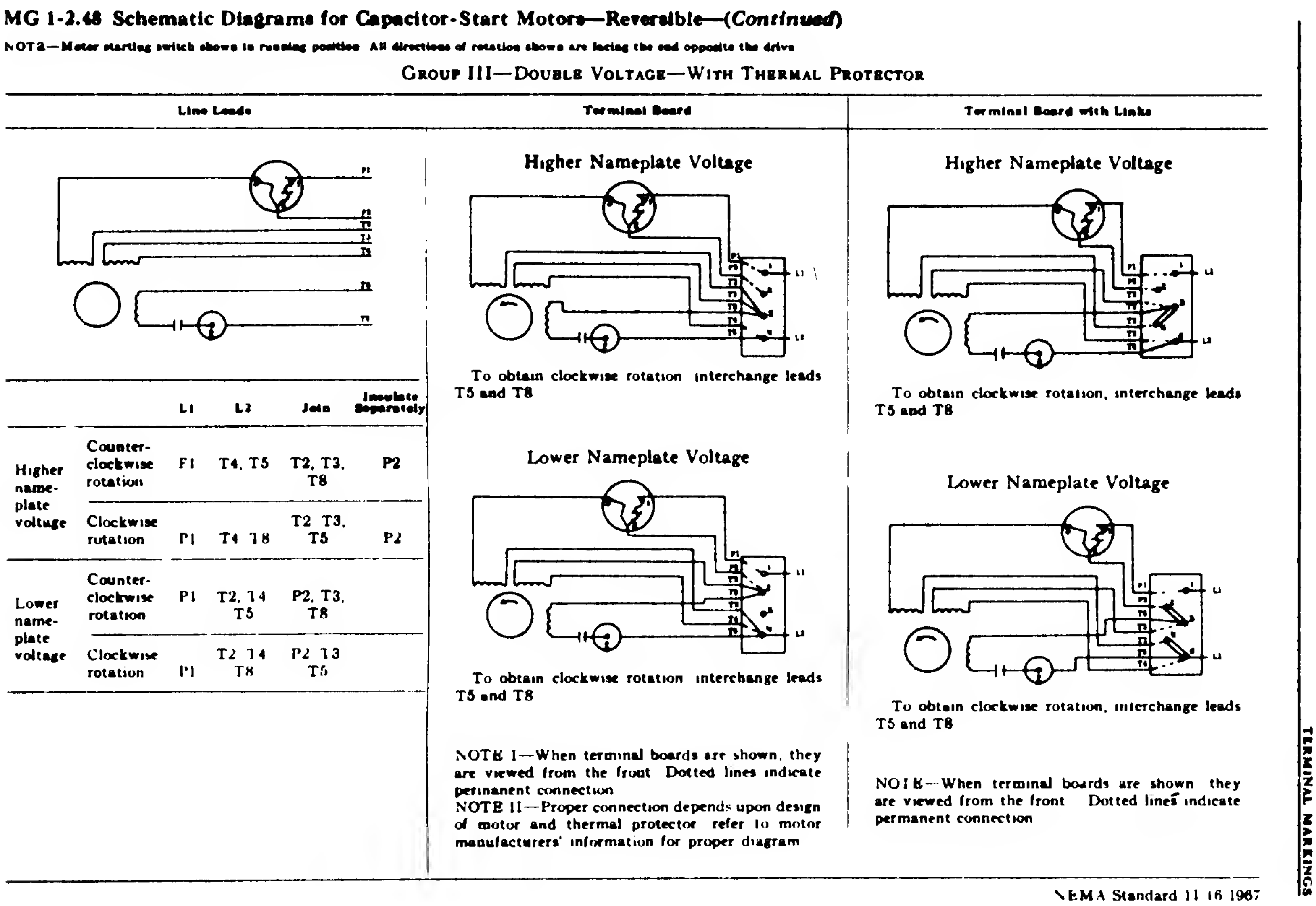


To obtain clockwise rotation, interchange leads T5 and T8

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

TERMINAL MARKINGS

Fig. 1-121d. Schematic diagram for capacitor-start motors—reversible (*continued*).



MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—(*Continued*)

NOTE—Motor starting switch shown in running position All directions of rotation shown are facing the end opposite the drive

GROUP III—DOUBLE VOLTAGE—WITH THERMAL PROTECTOR

Line Leads

		L1	L2	Join	Insulate Separately
Higher name-plate voltage	Counter-clockwise rotation	P1	T4, T5	T2, T3, T8	P2
	Clockwise rotation	P1	T4 T8	T2 T3, T5	P2
Lower name-plate voltage	Counter-clockwise rotation	P1	T2, T4 T5	P2, T3, T8	
	Clockwise rotation	P1	T2 T4 T8	P2 T3 T5	

Terminal Board

Higher Nameplate Voltage

To obtain clockwise rotation interchange leads T5 and T8

Lower Nameplate Voltage

To obtain clockwise rotation interchange leads T5 and T8

NOTE I—When terminal boards are shown, they are viewed from the front Dotted lines indicate permanent connection
NOTE II—Proper connection depends upon design of motor and thermal protector refer to motor manufacturers' information for proper diagram

Terminal Board with Links

Higher Nameplate Voltage

To obtain clockwise rotation, interchange leads T5 and T8

Lower Nameplate Voltage

To obtain clockwise rotation, interchange leads T5 and T8

NOTE—When terminal boards are shown they are viewed from the front Dotted lines indicate permanent connection

NEMA Standard 11 16 1967

TERMINAL MARKINGS

Fig. 1-121e. Schematic diagram for capacitor-start motors—reversible (*continued*).

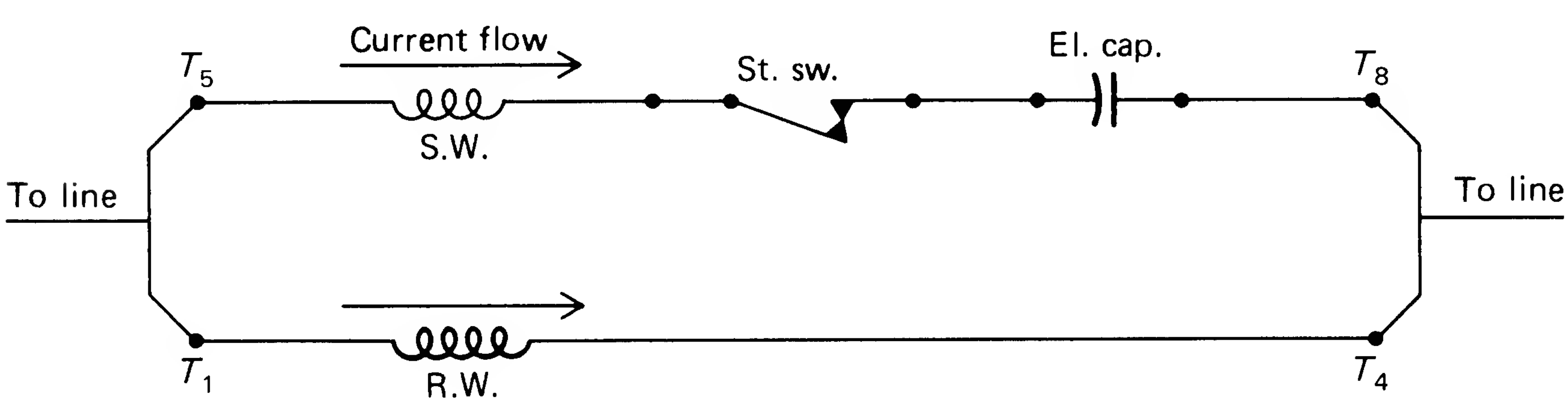


Fig. 1-122. Schematic diagram showing the connection for clockwise rotation, facing the end opposite the shaft. All numbered leads are accessible or come out of the motor.

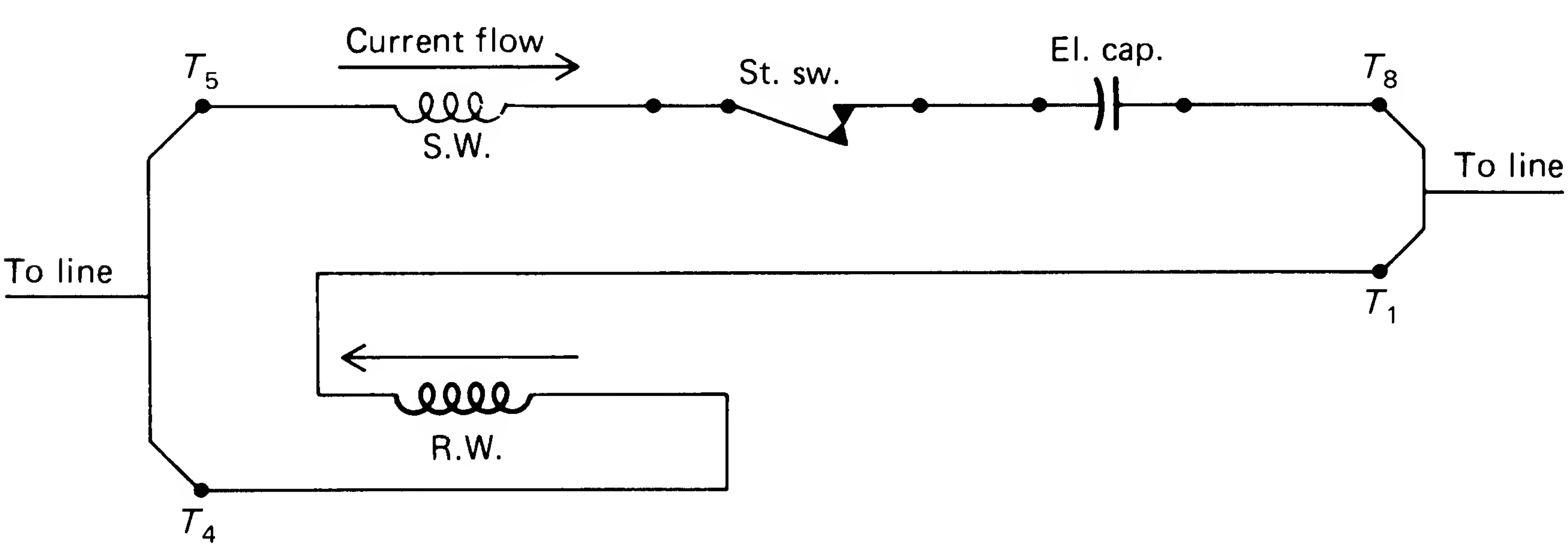


Fig. 1-123. Schematic diagram showing the connection for counterclockwise rotation. All numbered leads are accessible or come out of the motor.

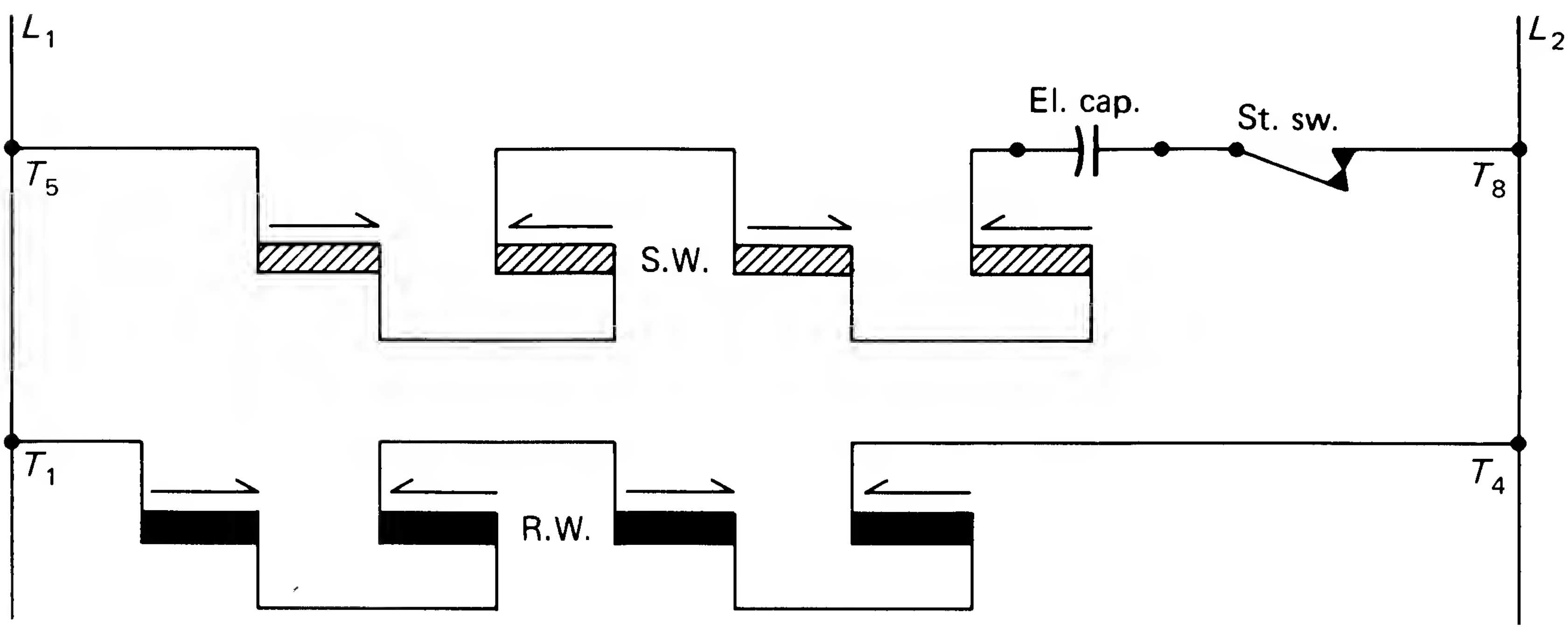


Fig. 1-124. Straight-line diagram of a four-pole, capacitor-start motor, connected short jumper.

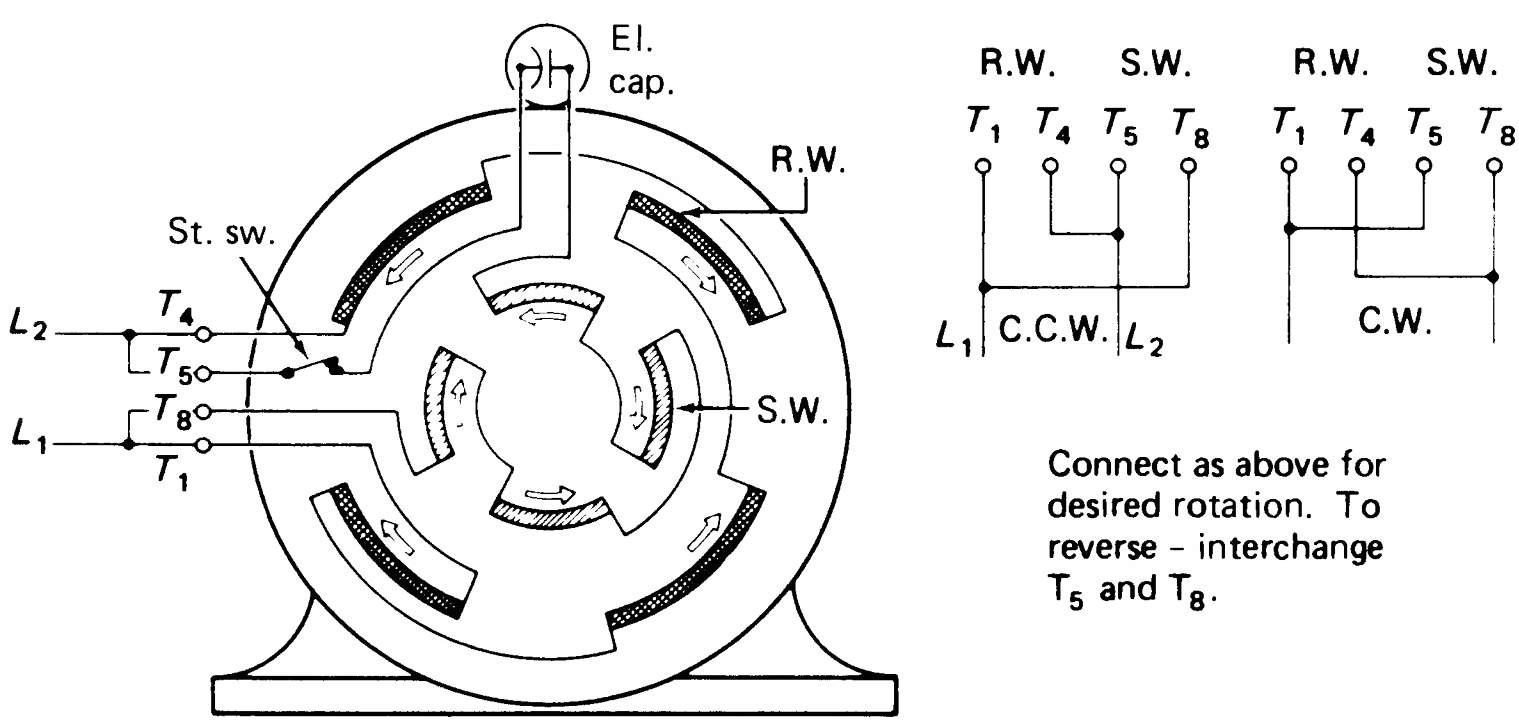


Fig. 1-125. Connection diagram of a four-pole capacitor-start motor.

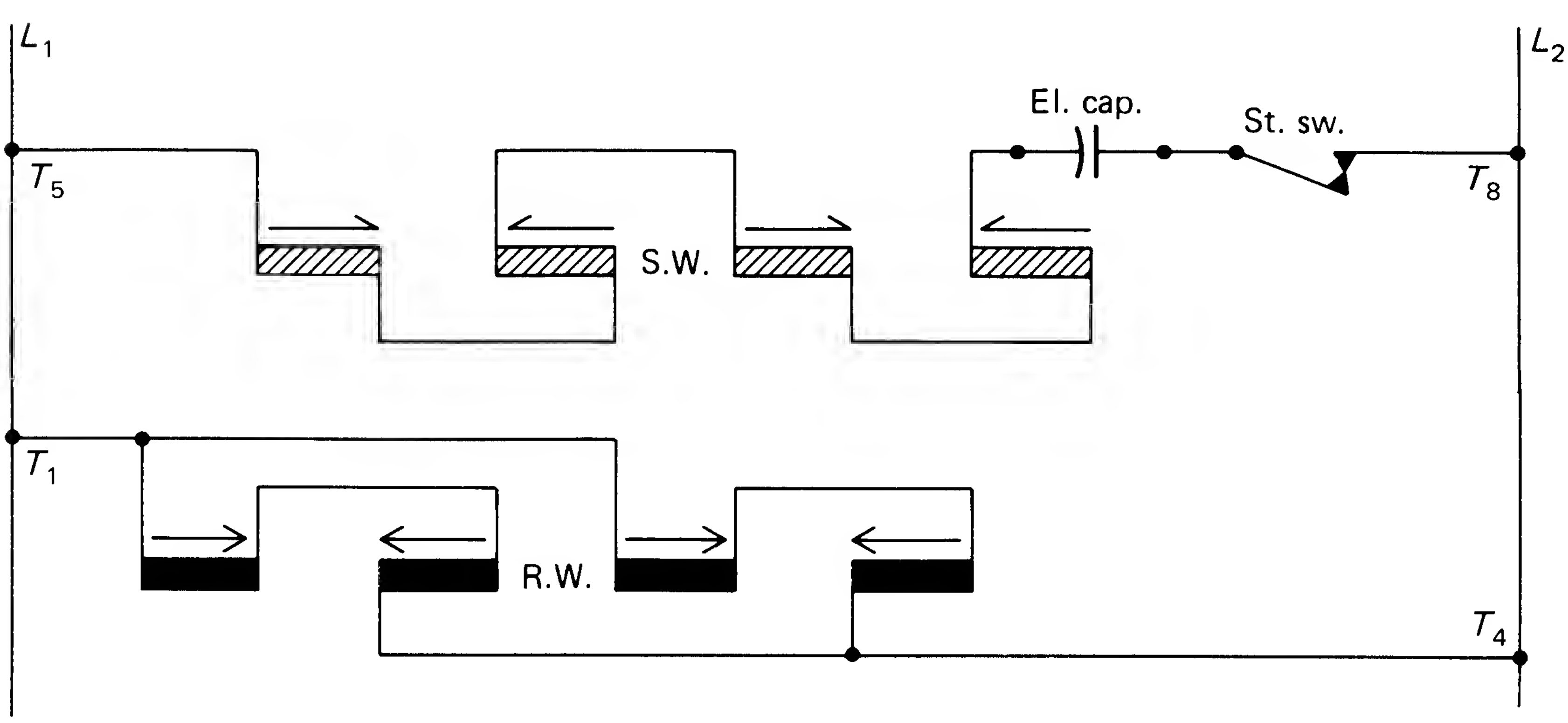


Fig. 1-126. Straight-line diagram of a four-pole, two-circuit, short jumper, capacitor-start motor.

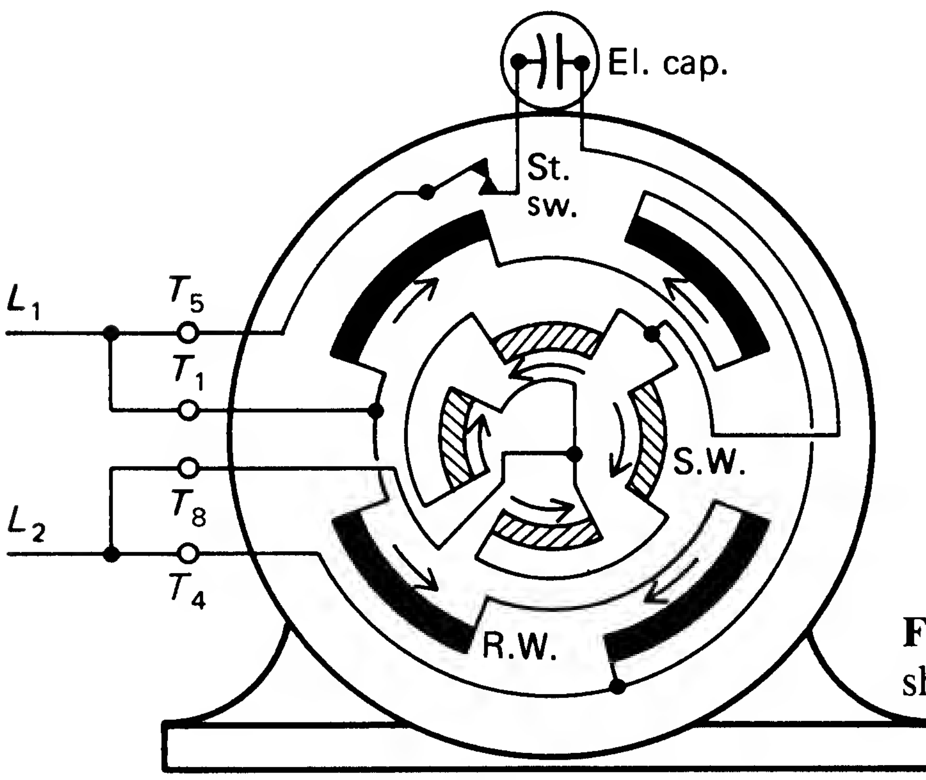


Fig. 1–127. Four-pole, two-circuit, short jumper, capacitor motor.

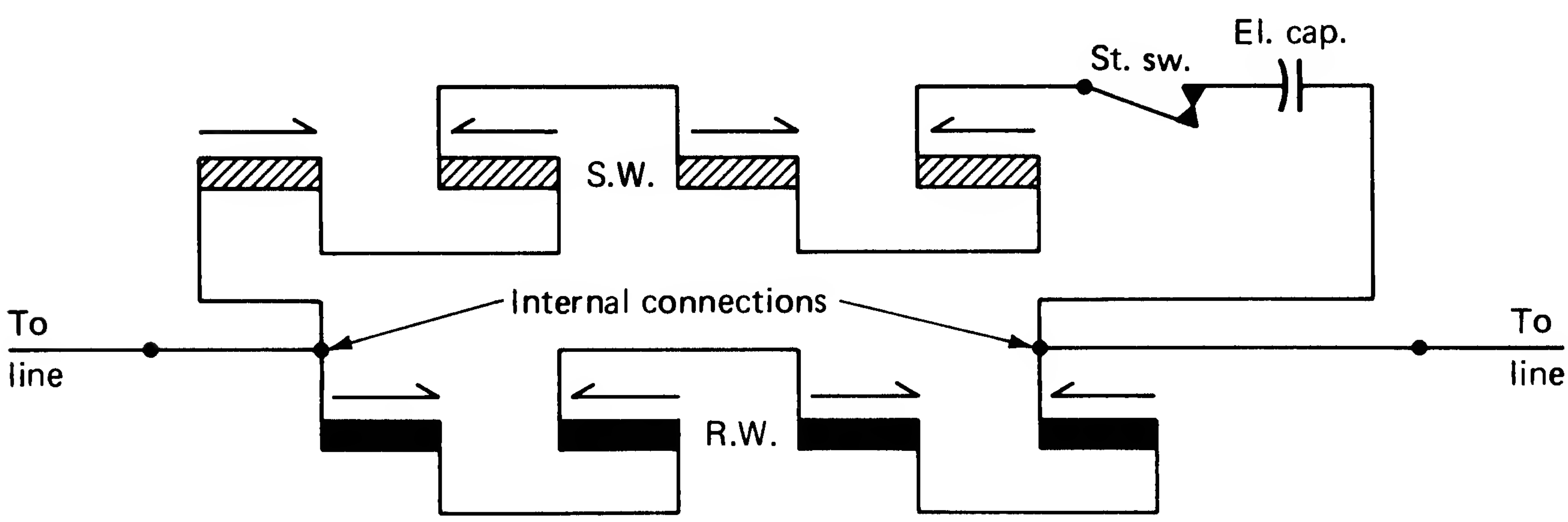


Fig. 1–128. Nonreversible single-voltage motor. Rotation will be from a start-winding pole group to the nearest like-polarity pole group of the run winding.

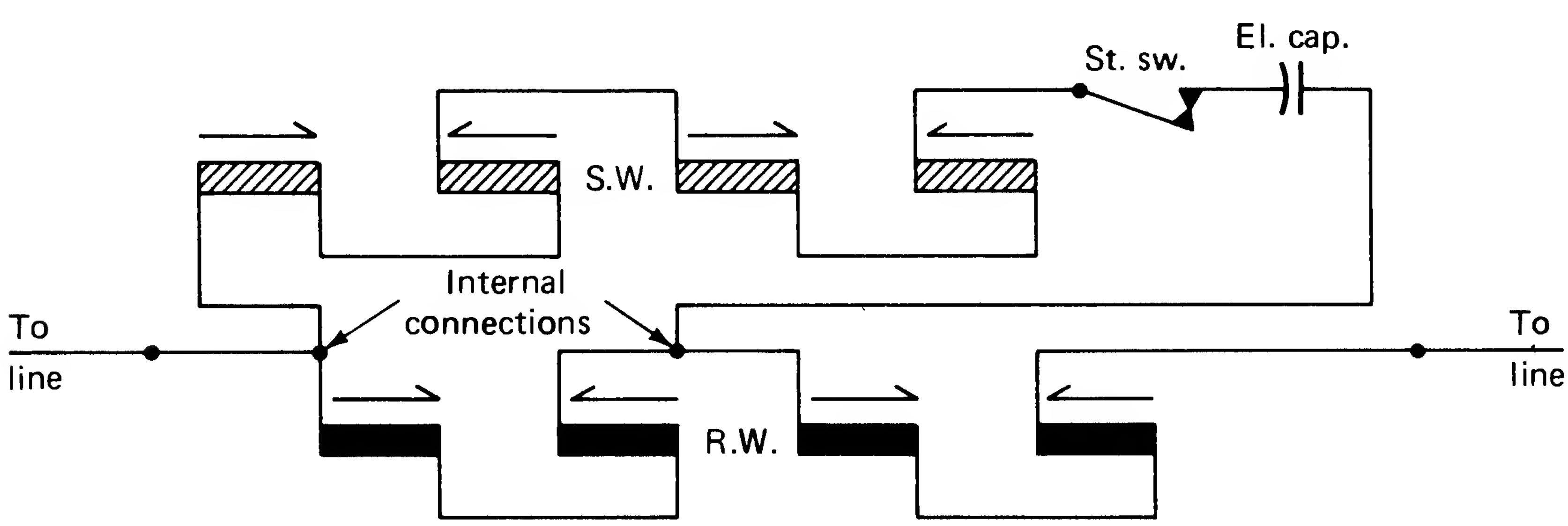


Fig. 1–129. Nonreversible high-voltage motor with a low-voltage–rated start winding, connected to the center of the run winding.

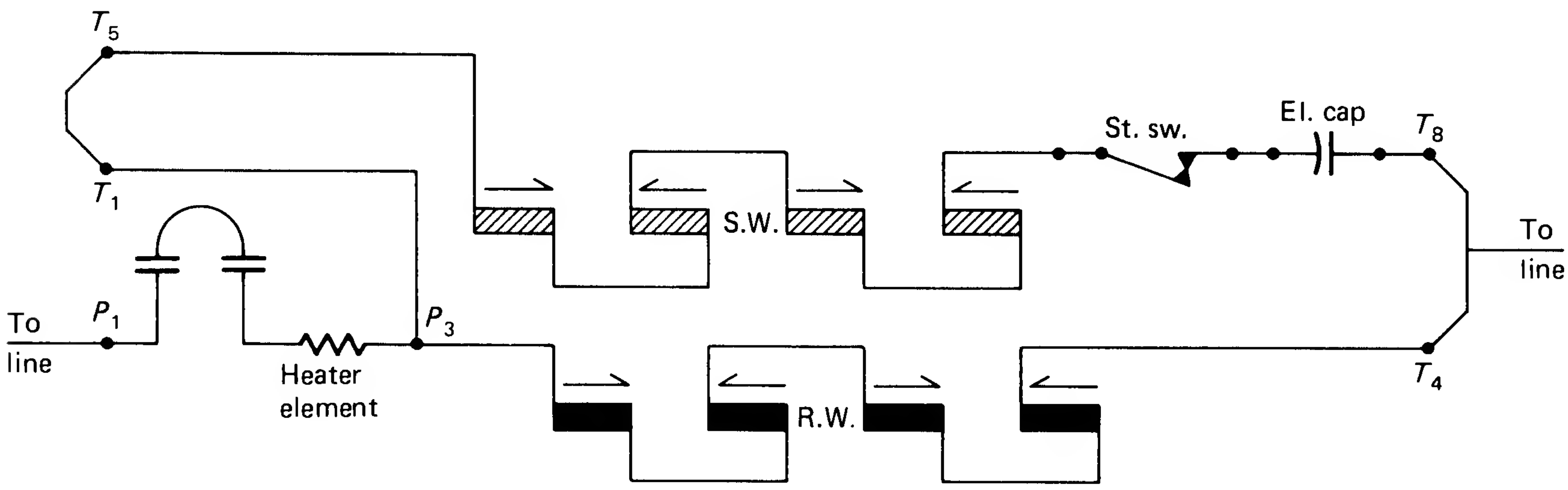


Fig. 1-130. Single-voltage capacitor motor with an overload protector. The overload protector may be located inside the motor or in the junction box outside the motor.

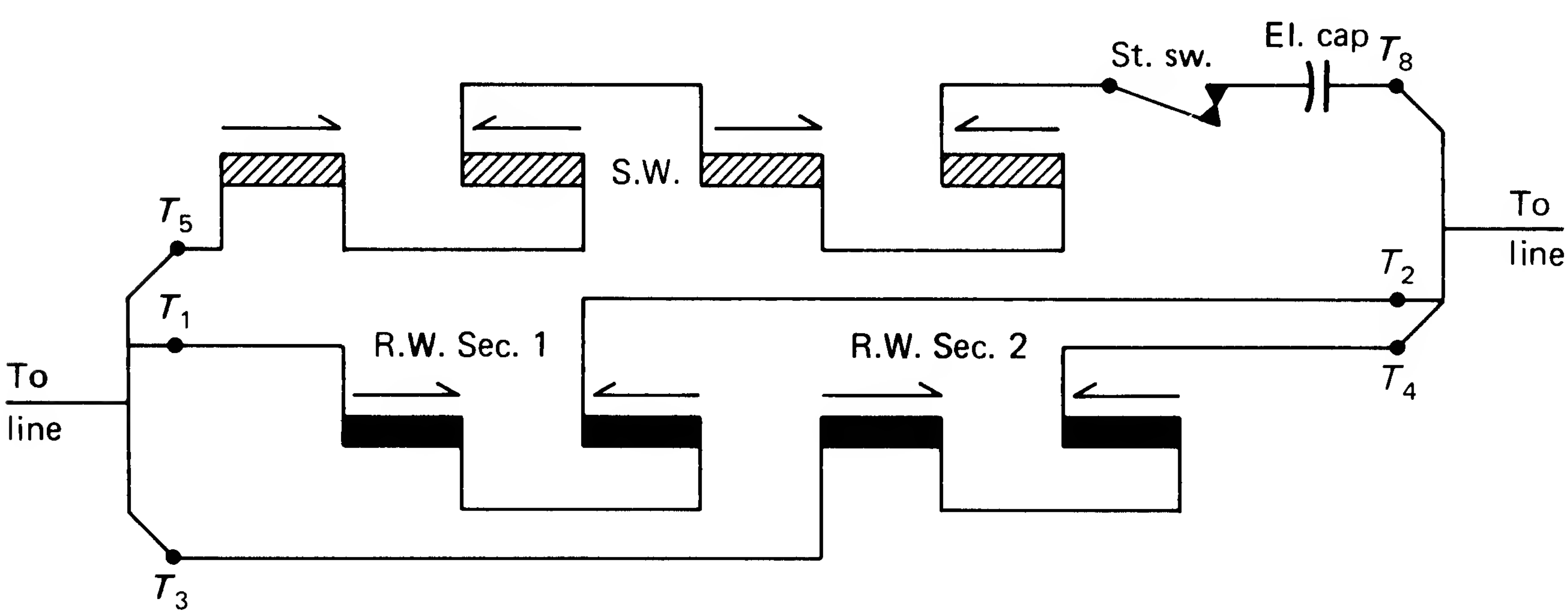


Fig. 1-131. Two-voltage capacitor-start motor connected for low voltage. This is a short jumper connection.

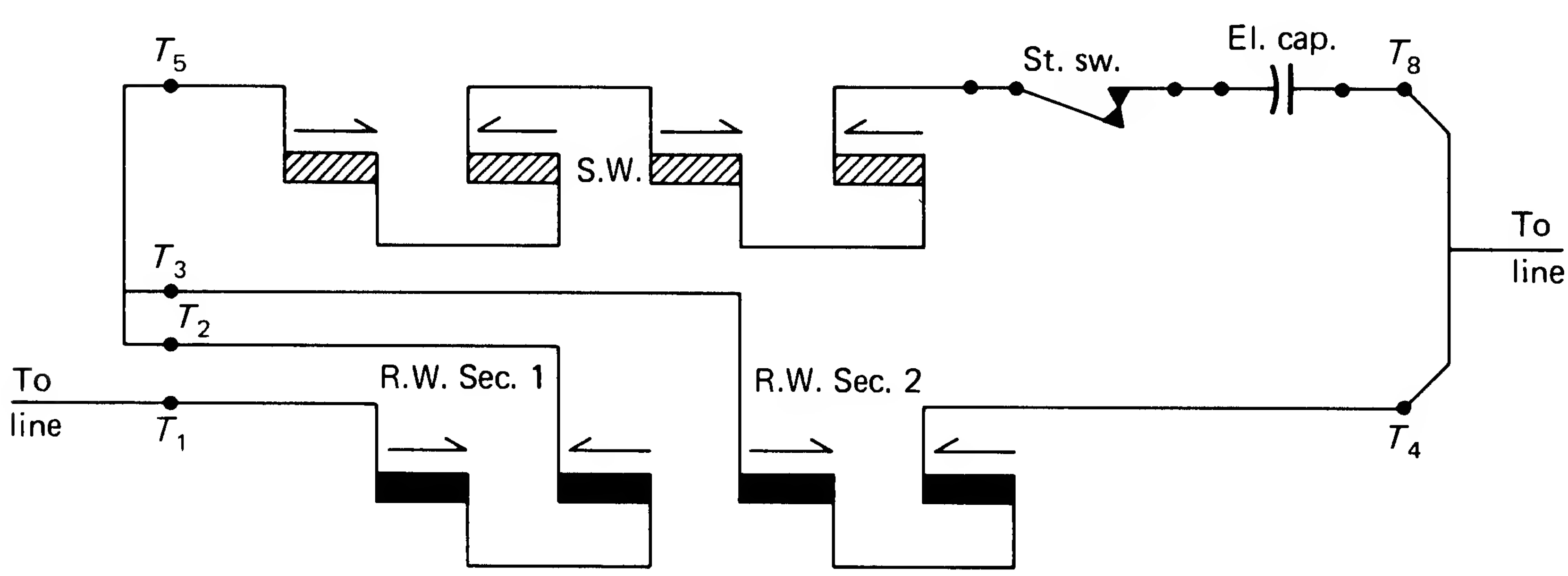


Fig. 1-132. Two-voltage motor connected for high voltage.

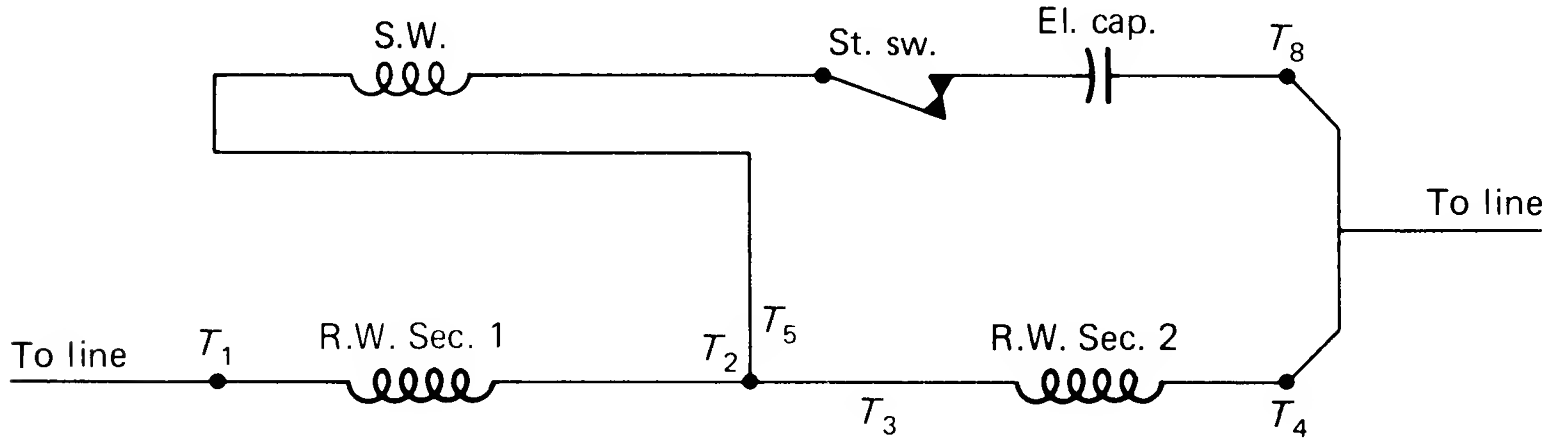
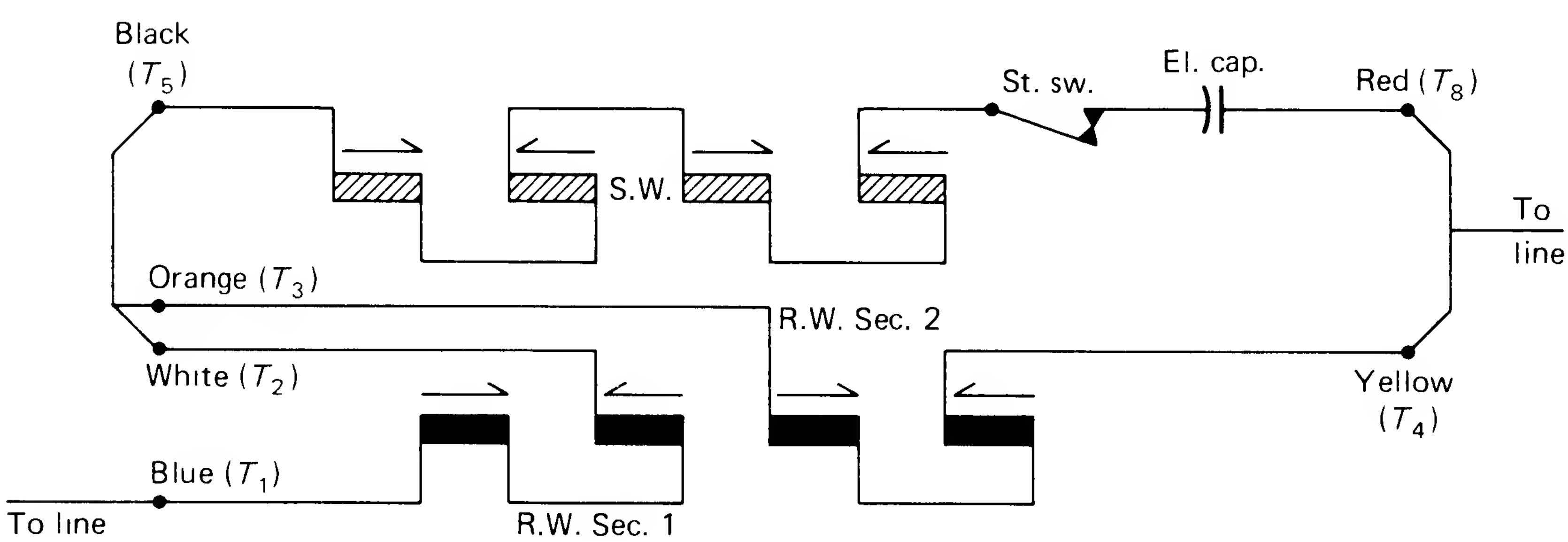
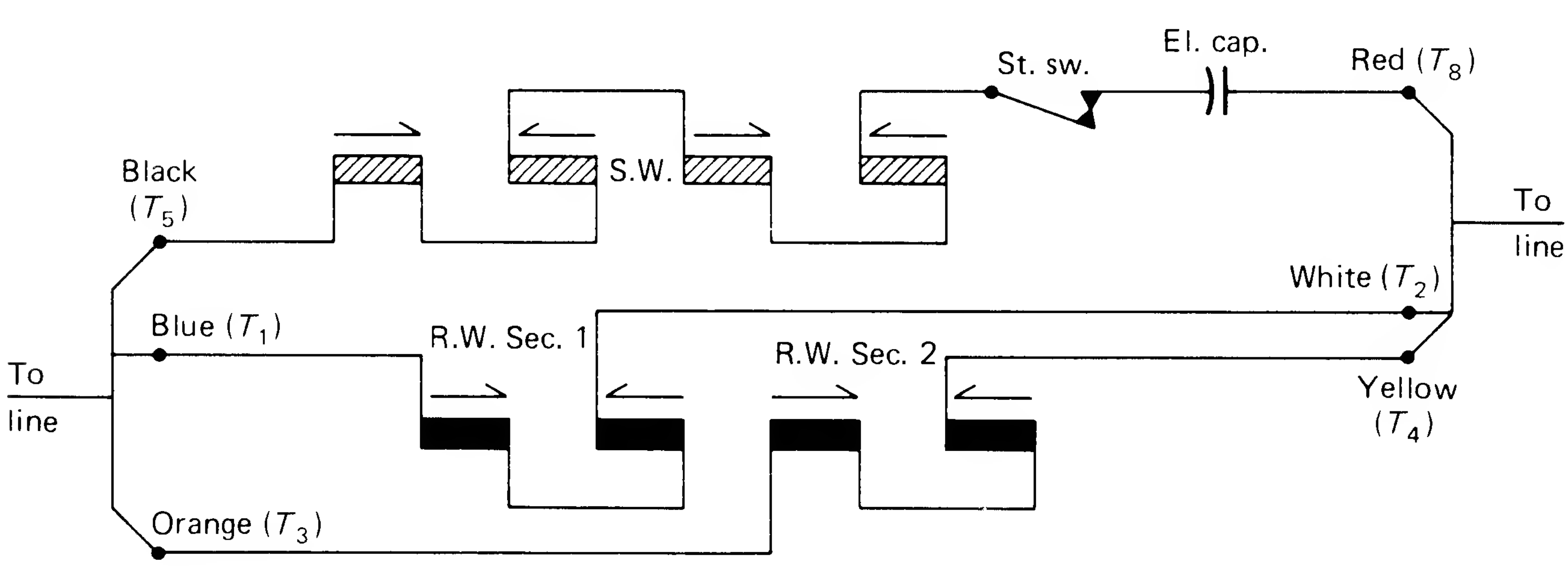


Fig. 1–133. Schematic of a two-voltage motor connected for high voltage.



a) High voltage connection



b) Low-voltage connection

Fig. 1–134. High- and low-voltage connections using colored wires instead of numbers.

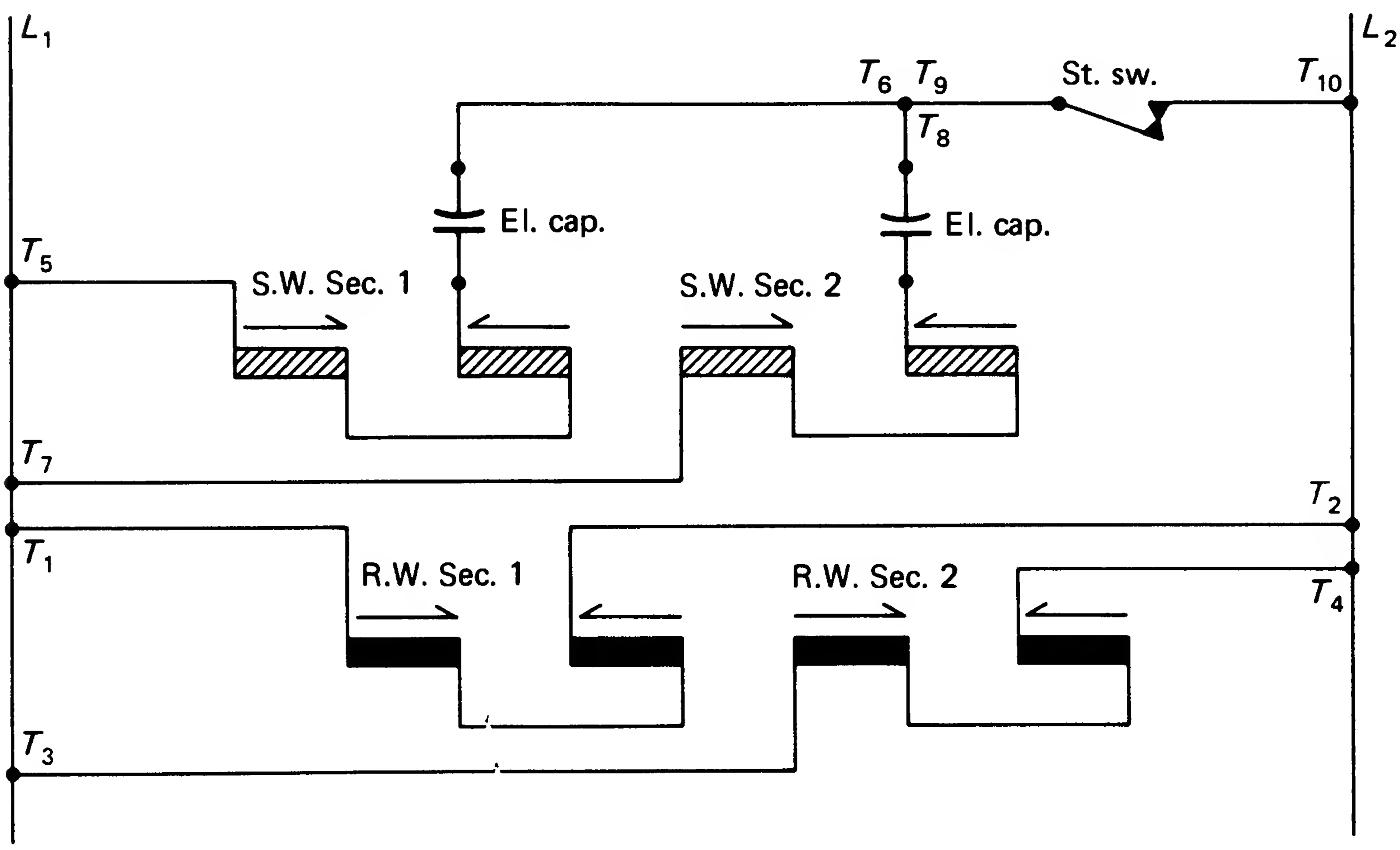


Fig. 1-135. Two-voltage capacitor-start motor-connection with two capacitors and one switch. This motor is connected for low voltage. T_9 and T_{10} are connected to both sides of the centrifugal switch and brought out of the motor.

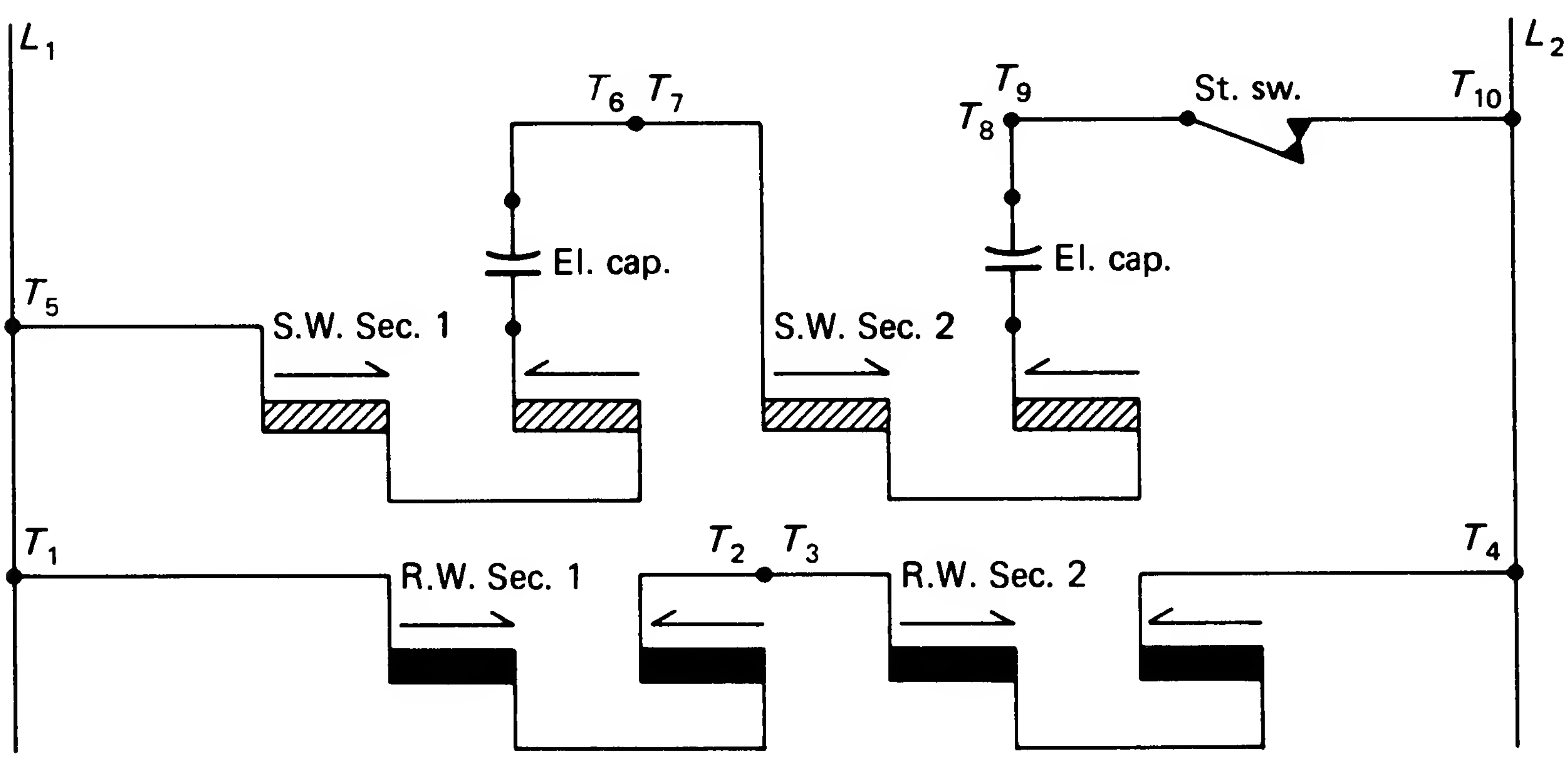


Fig. 1-136. Two-voltage capacitor-start motor connection with two capacitors and one switch. This motor is connected for high voltage. T_9 and T_{10} keep the start winding and the capacitors in series with the centrifugal switch.

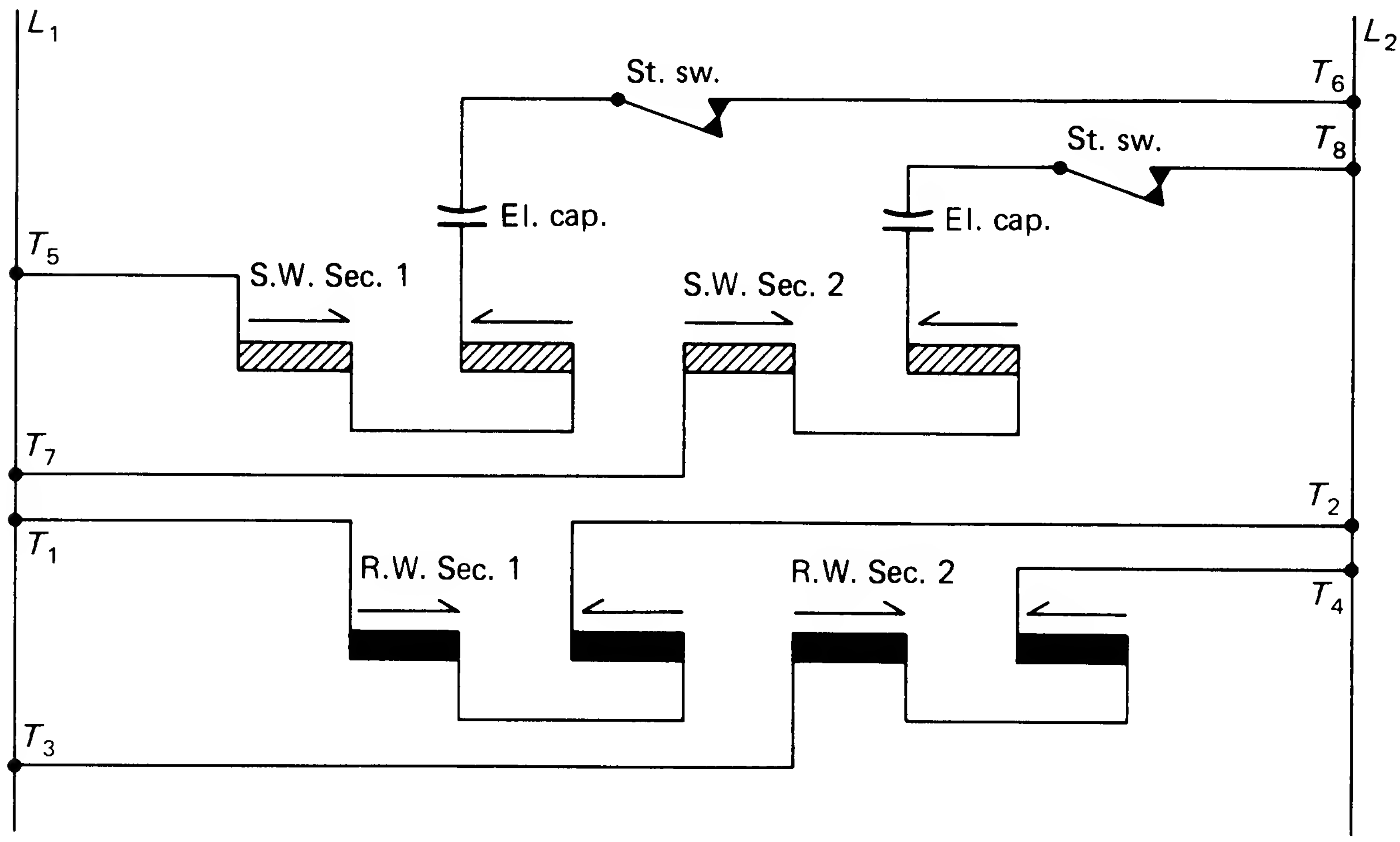


Fig. 1–137. Two-voltage capacitor-start motor connection with two capacitors and two switches. This motor is connected for low voltage.

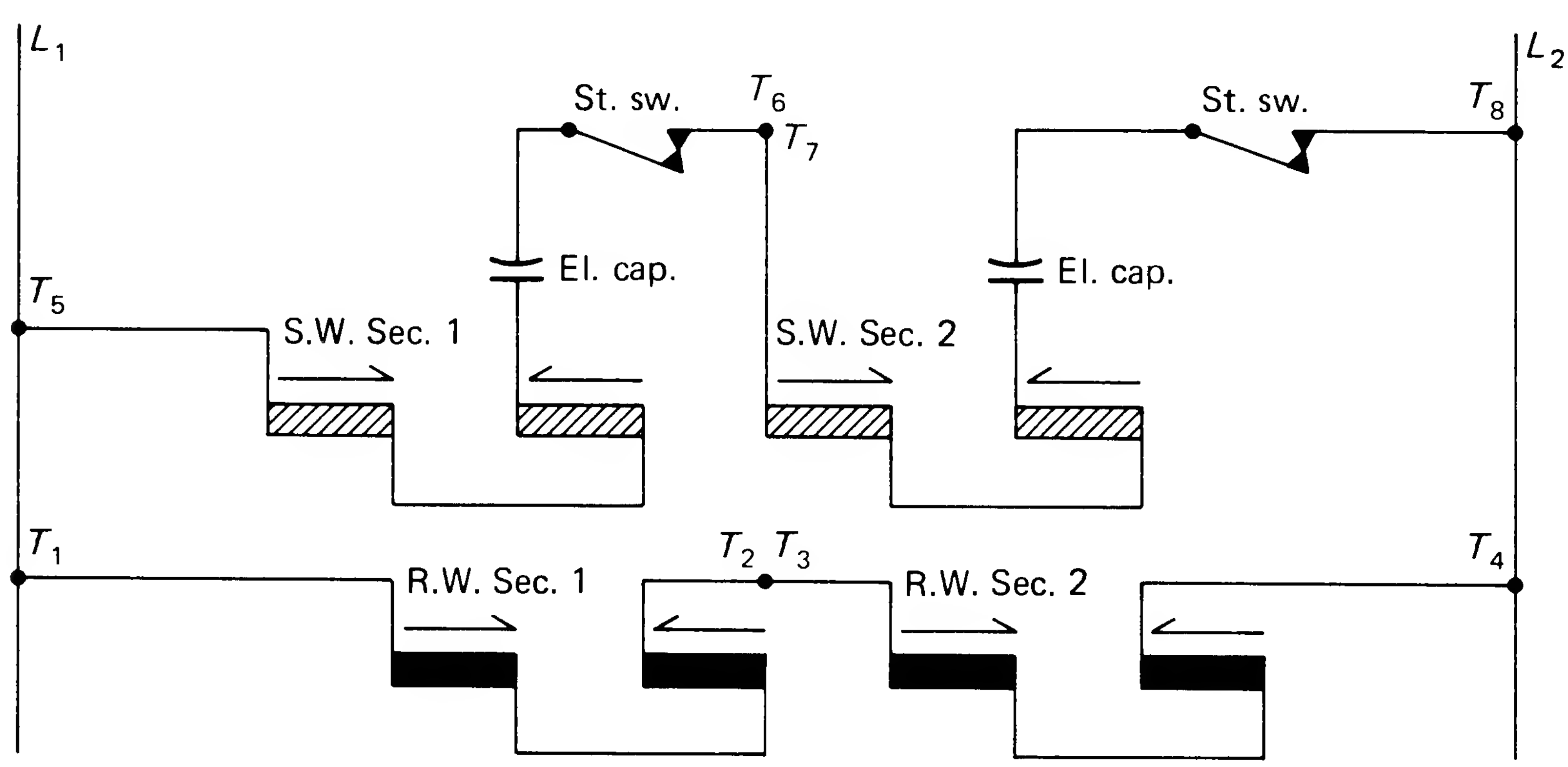


Fig. 1–138. Two-voltage capacitor-start motor connection with two capacitors and two switches. This motor is connected for high voltage.

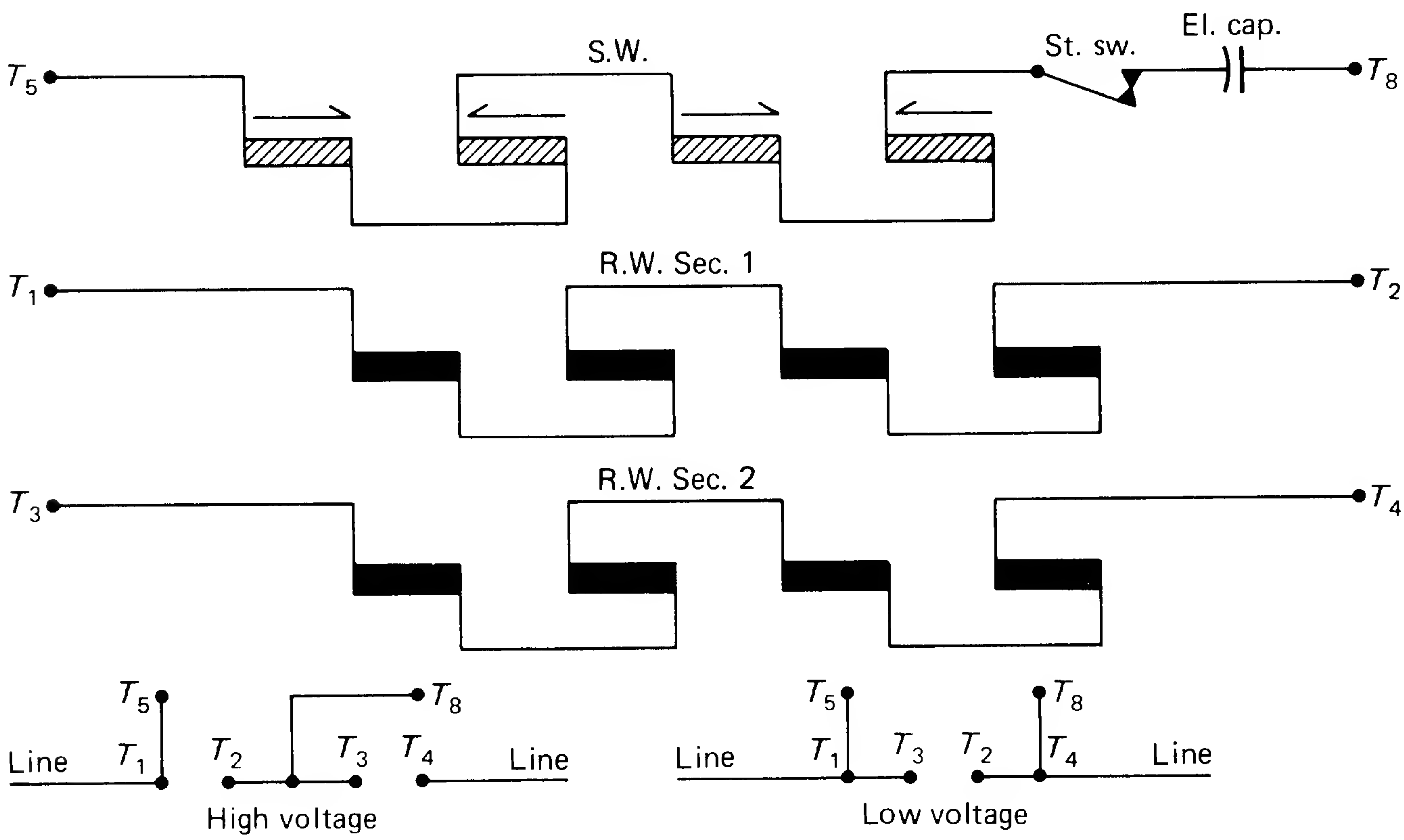


Fig. 1-139. Straight-line diagram of a four-pole, short jumper, two-voltage, capacitor-start motor with a layered run winding.

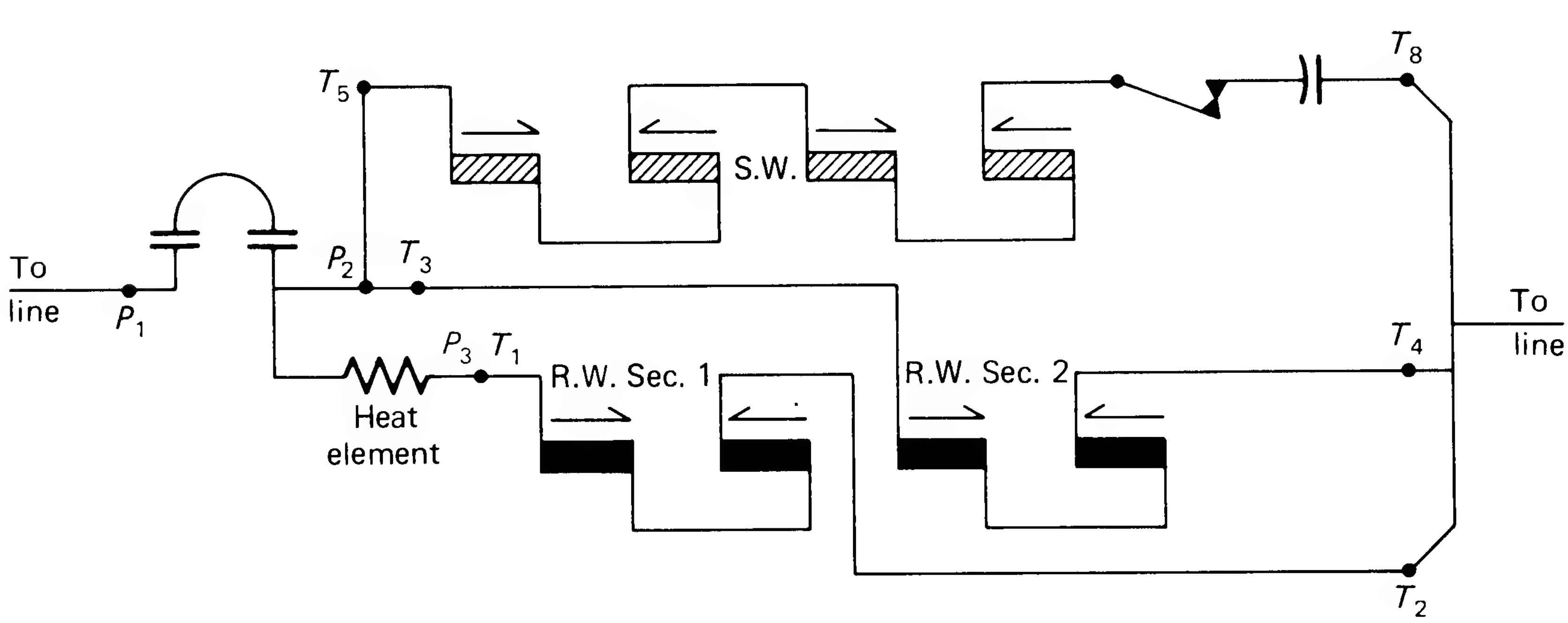


Fig. 1-140. Two-voltage capacitor-start motor with overload, connected for low voltage.

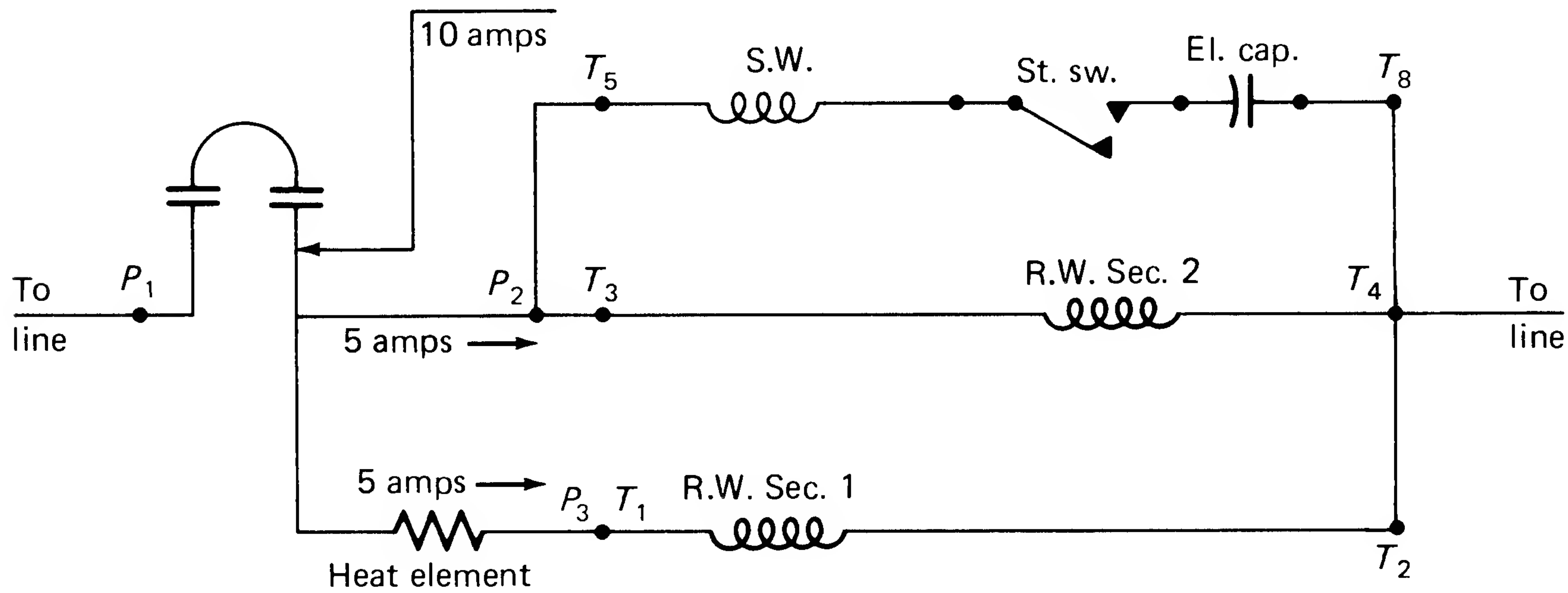


Fig. 1-141. Schematic of a two-voltage motor with overload, showing the path of the run current. Only half of the run current flows through the heat element of the thermal protector when the motor is connected for low voltage.

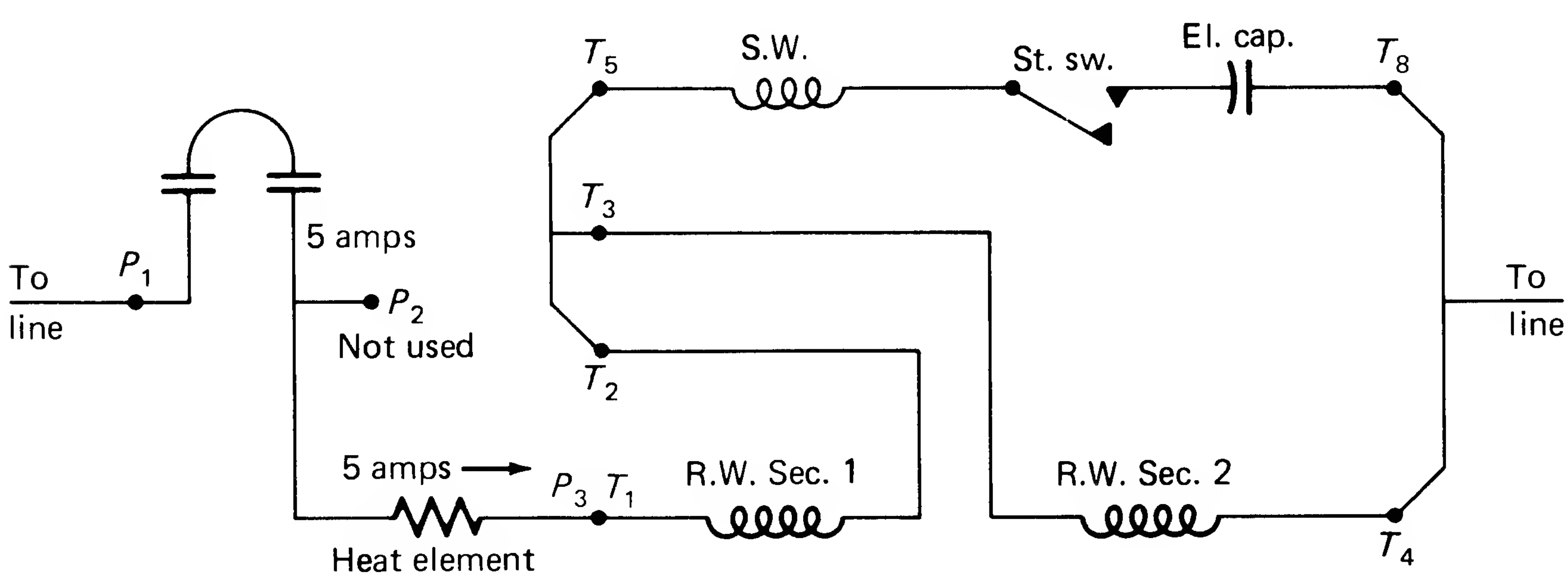


Fig. 1-142. Schematic of a two-voltage motor with an overload device, connected for high voltage. P_2 is not used with this connection. The nameplate amperes of a high-voltage connection will be half that of the low-voltage connection.

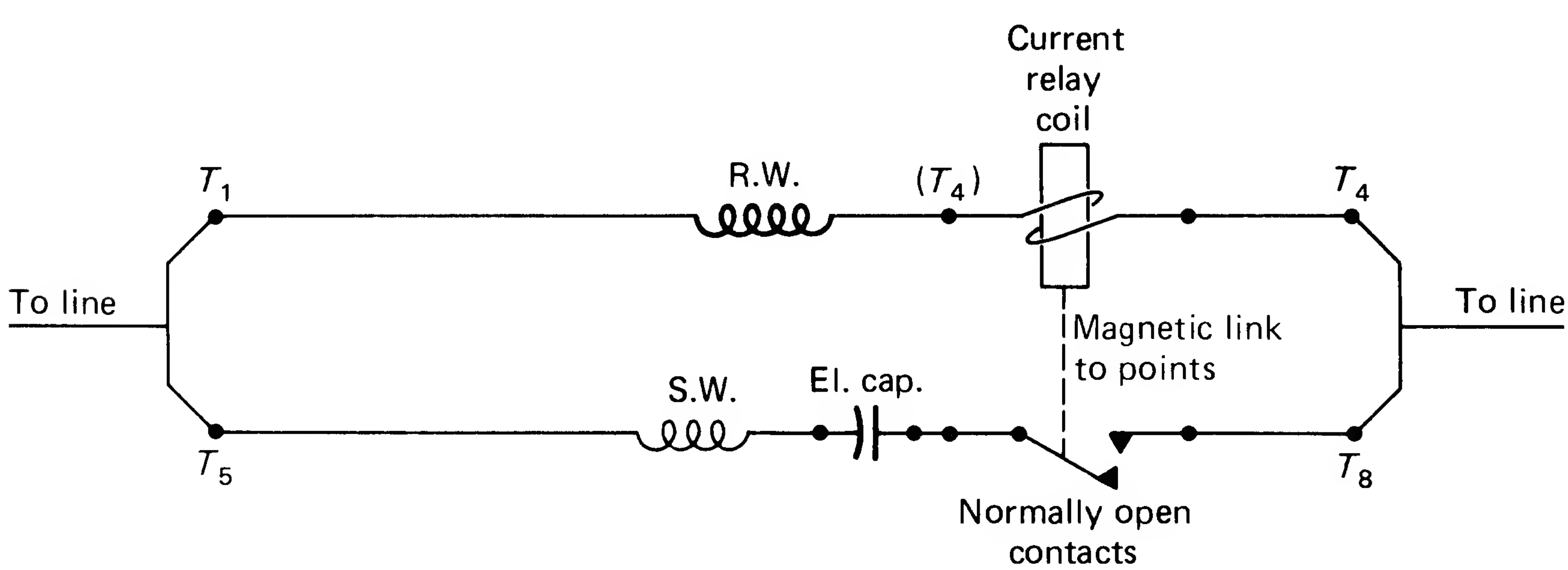


Fig. 1-143. Schematic of a single-voltage capacitor-start motor using a current relay to control the start winding.

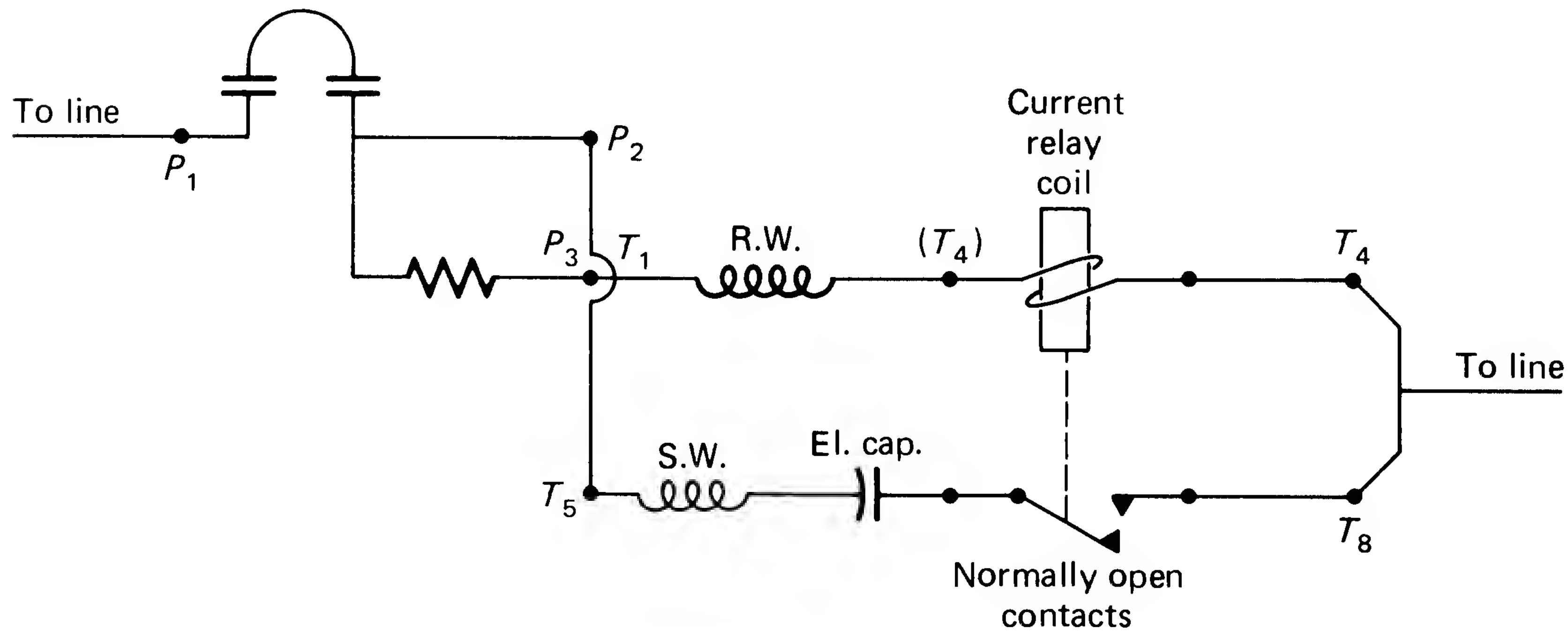


Fig. 1–144. Schematic of a single-voltage, capacitor-start motor with a thermal protector, using a current relay to control the start winding.

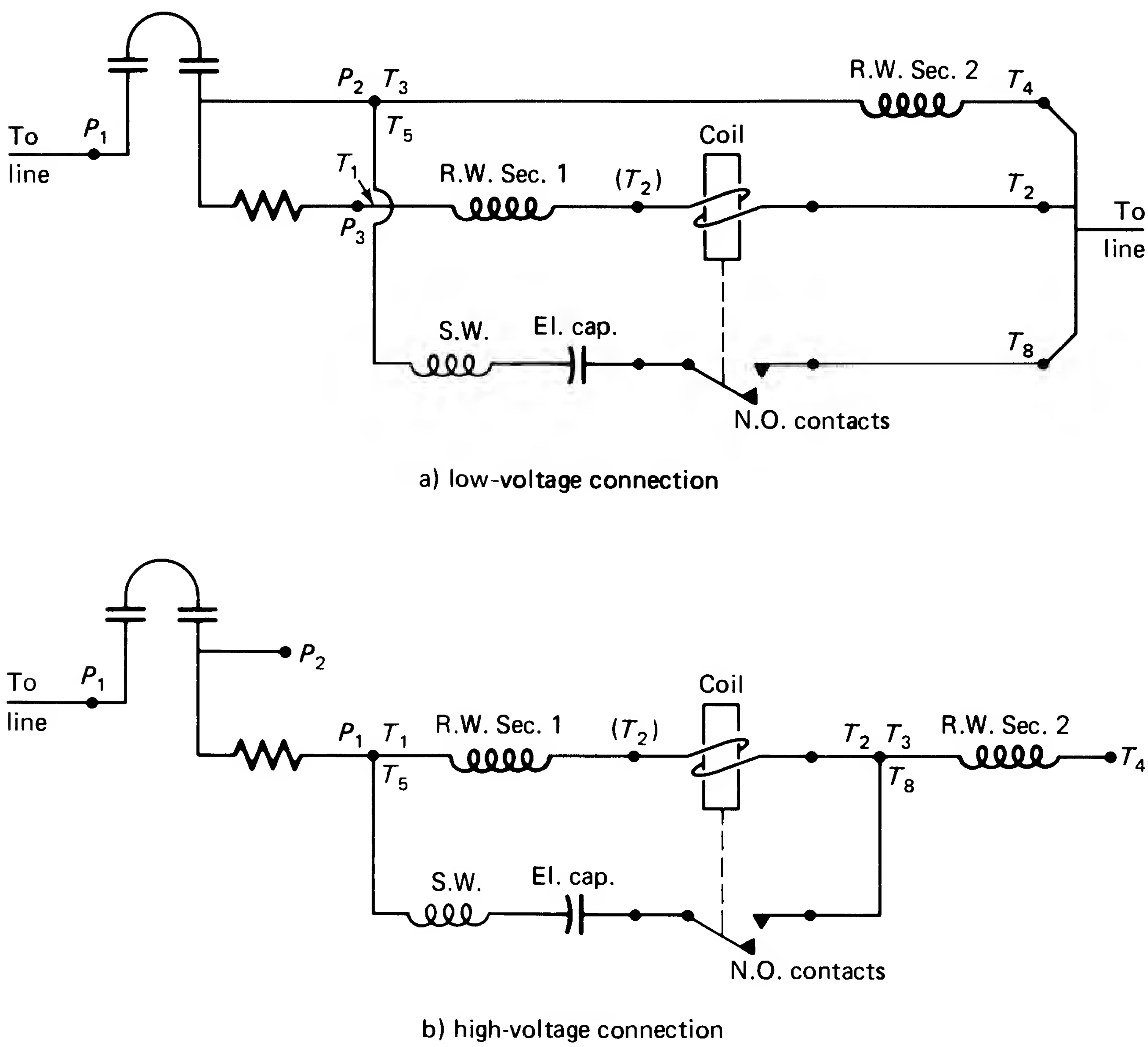


Fig. 1–145. Schematic of a two-voltage capacitor-start motor with a current relay controlling the start winding, (a) connected for low voltage and (b) connected for high voltage. The amperes through the coil of the relay is the same for both connections.

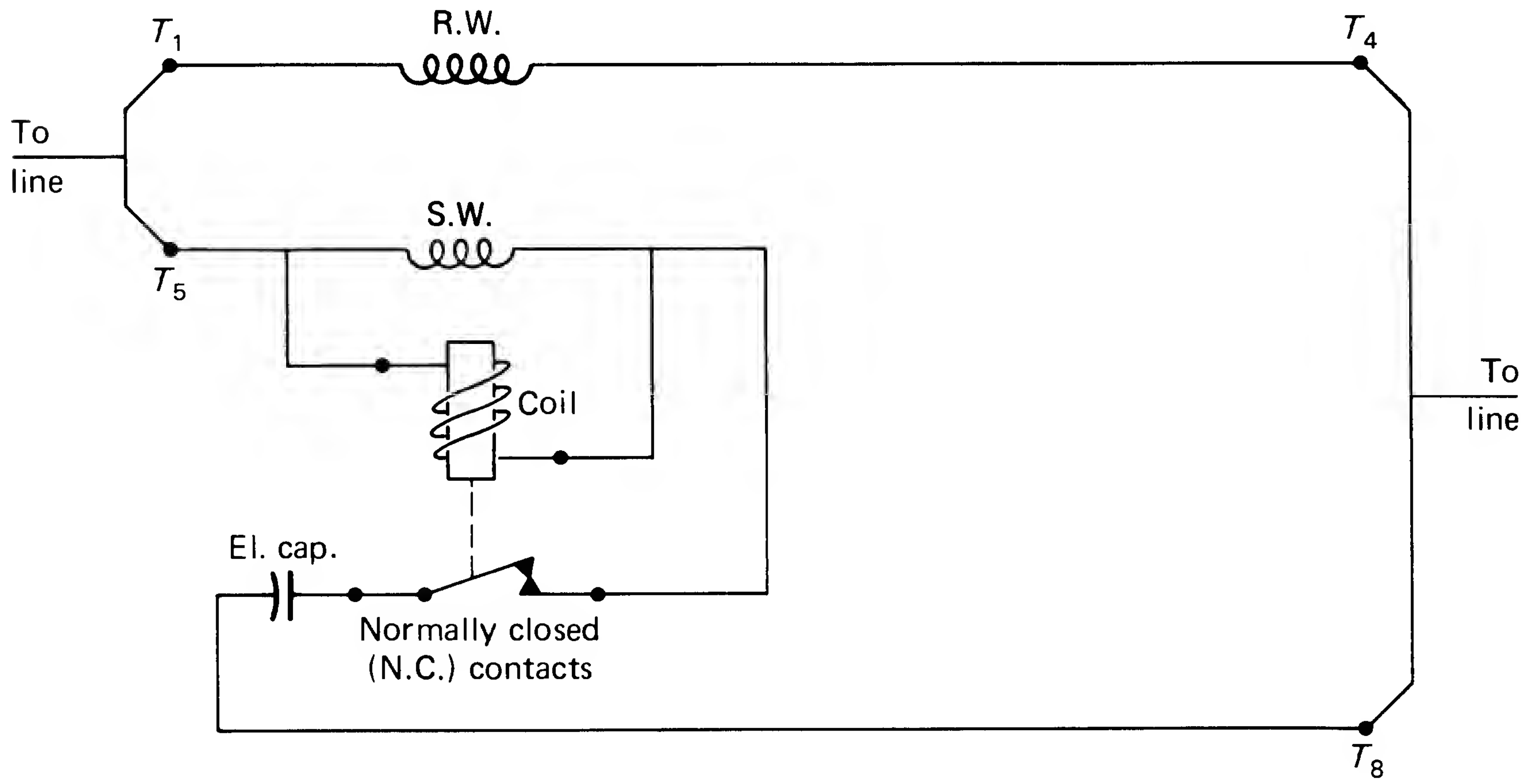


Fig. 1-146. Schematic of a capacitor-start motor with a potential relay controlling the start winding.

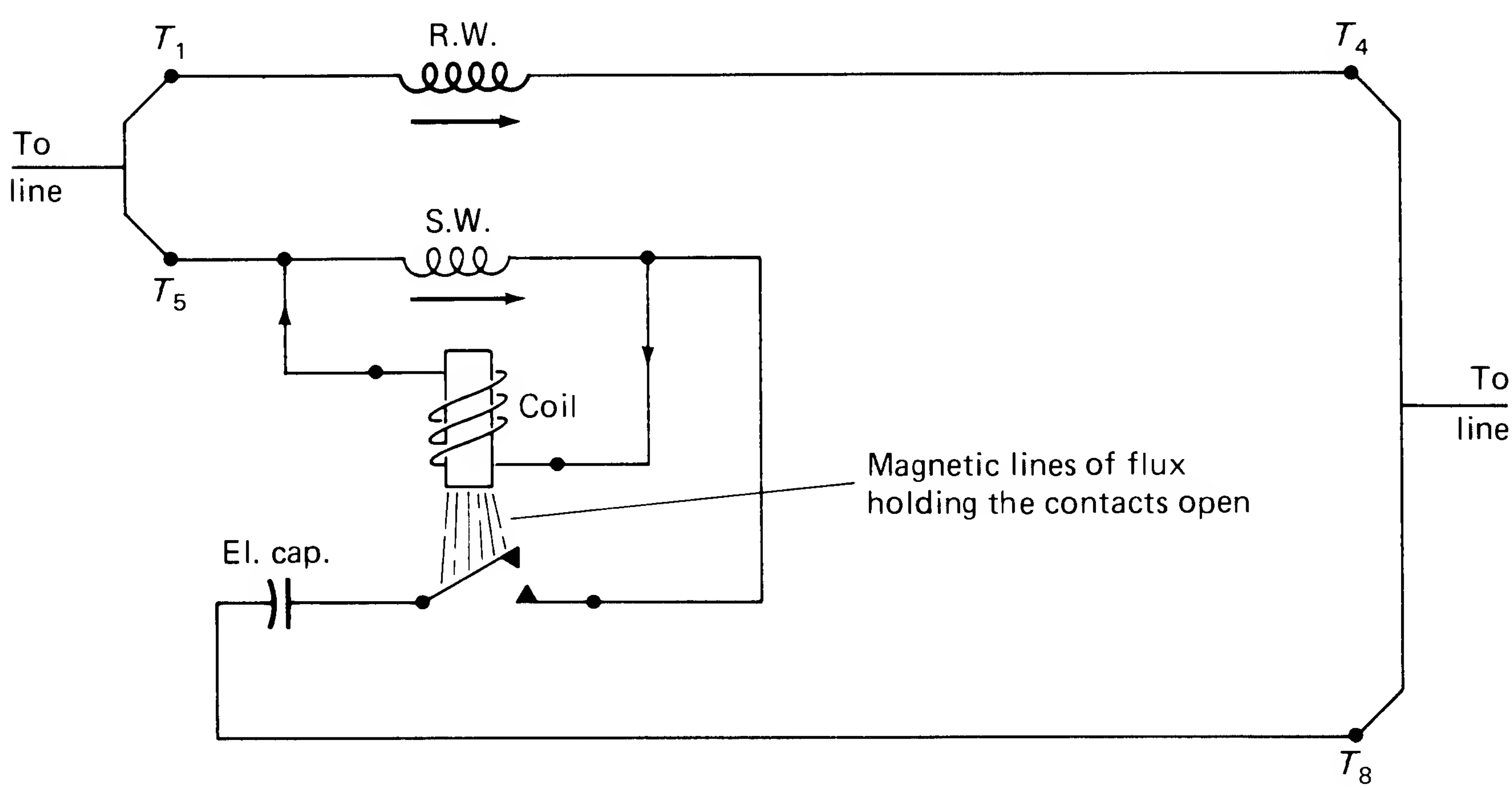


Fig. 1-147. Schematic showing the induced current flow in the start-winding relay-coil circuit of a capacitor-start motor with a potential-relay-controlled start winding.

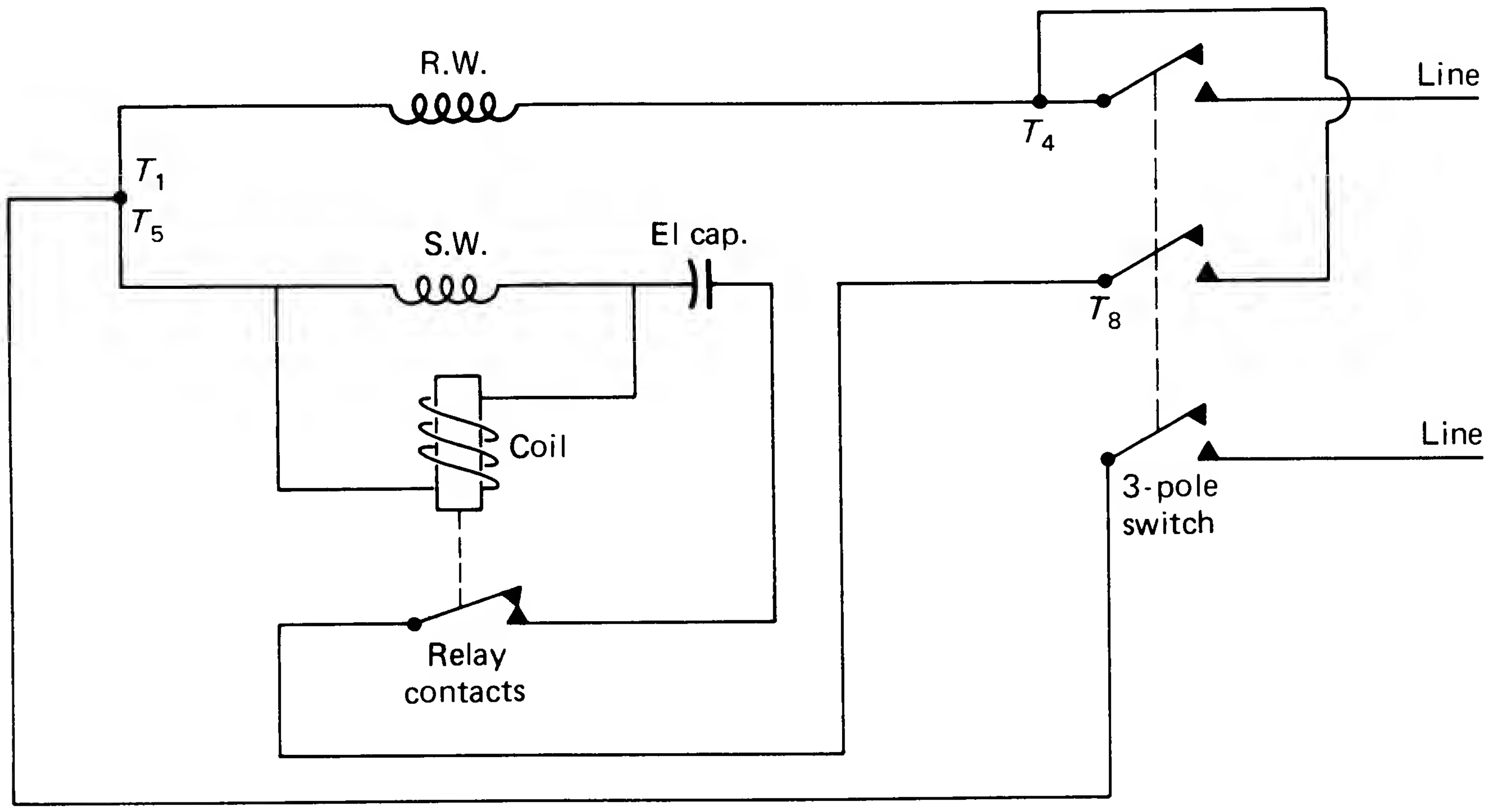


Fig. 1-148. A capacitor-start motor with a potential relay using a three-pole switch to isolate the start winding, preventing contact flutter.

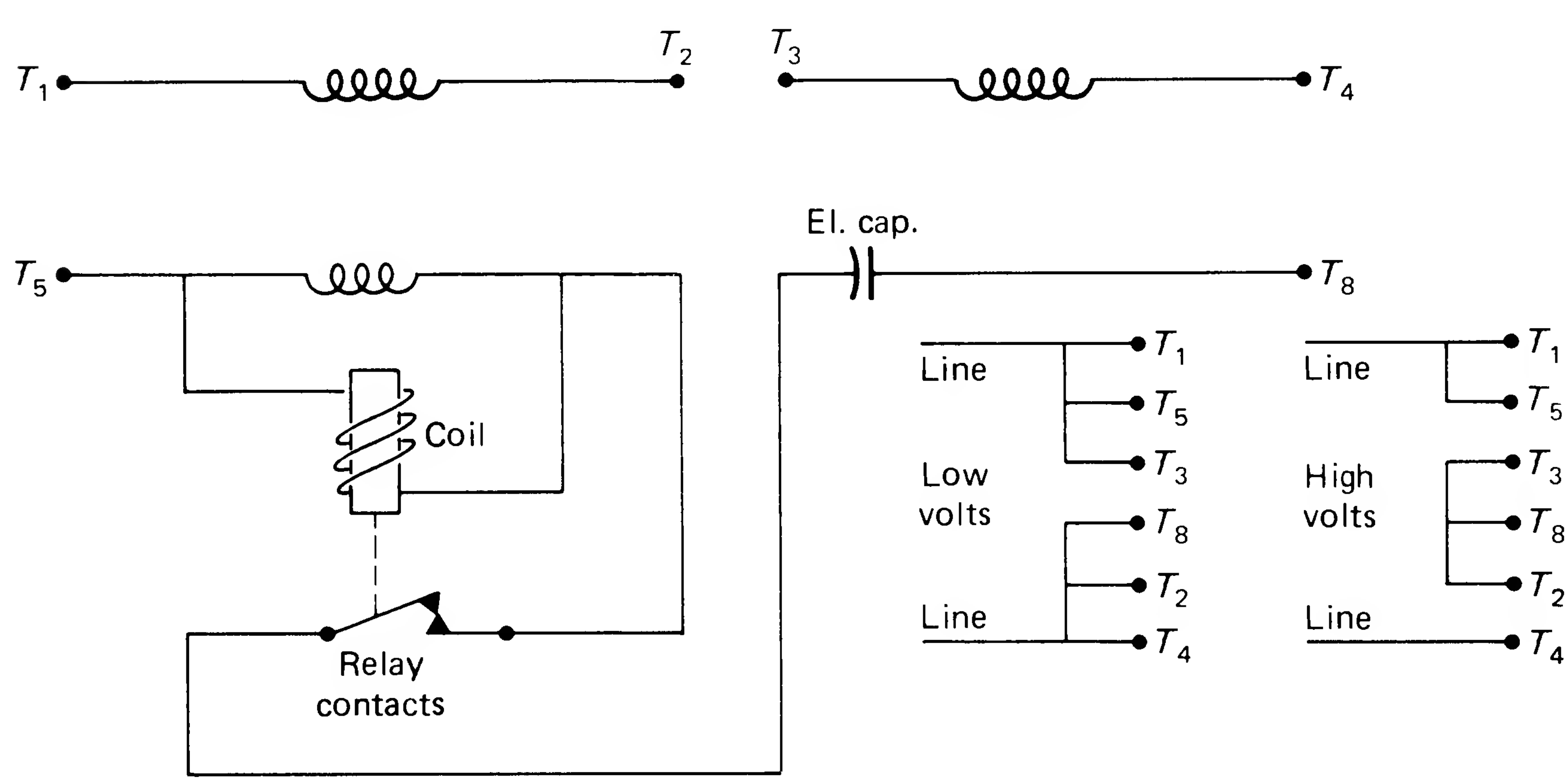


Fig. 1-149. Dual-voltage capacitor-start motor with a potential relay. The relay is rated for low voltage.

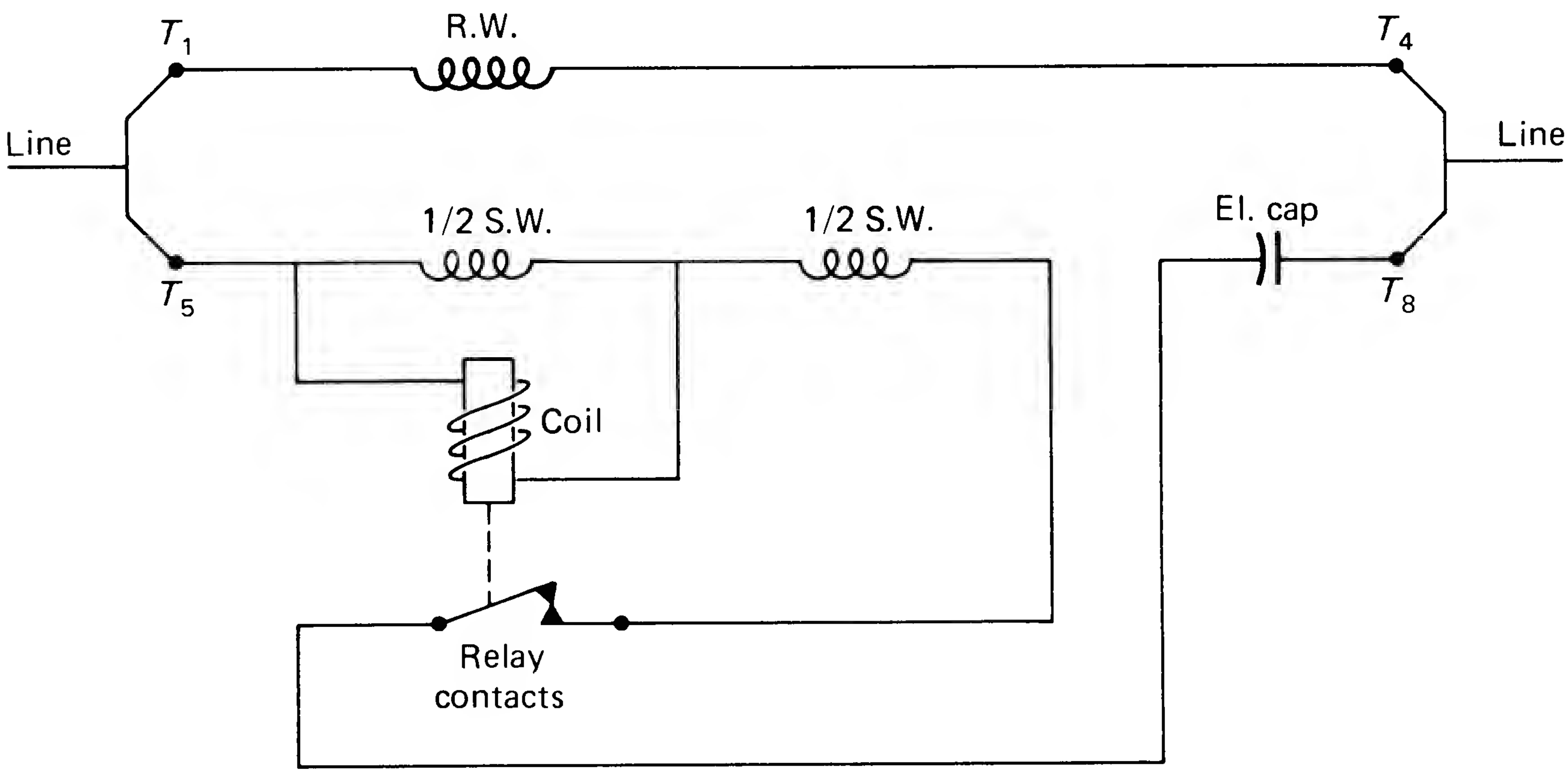


Fig. 1-150. A 240-volt capacitor-start motor with a potential relay. The coil of the relay is connected to the center connection of the start winding. The relay coil is rated for low voltage.

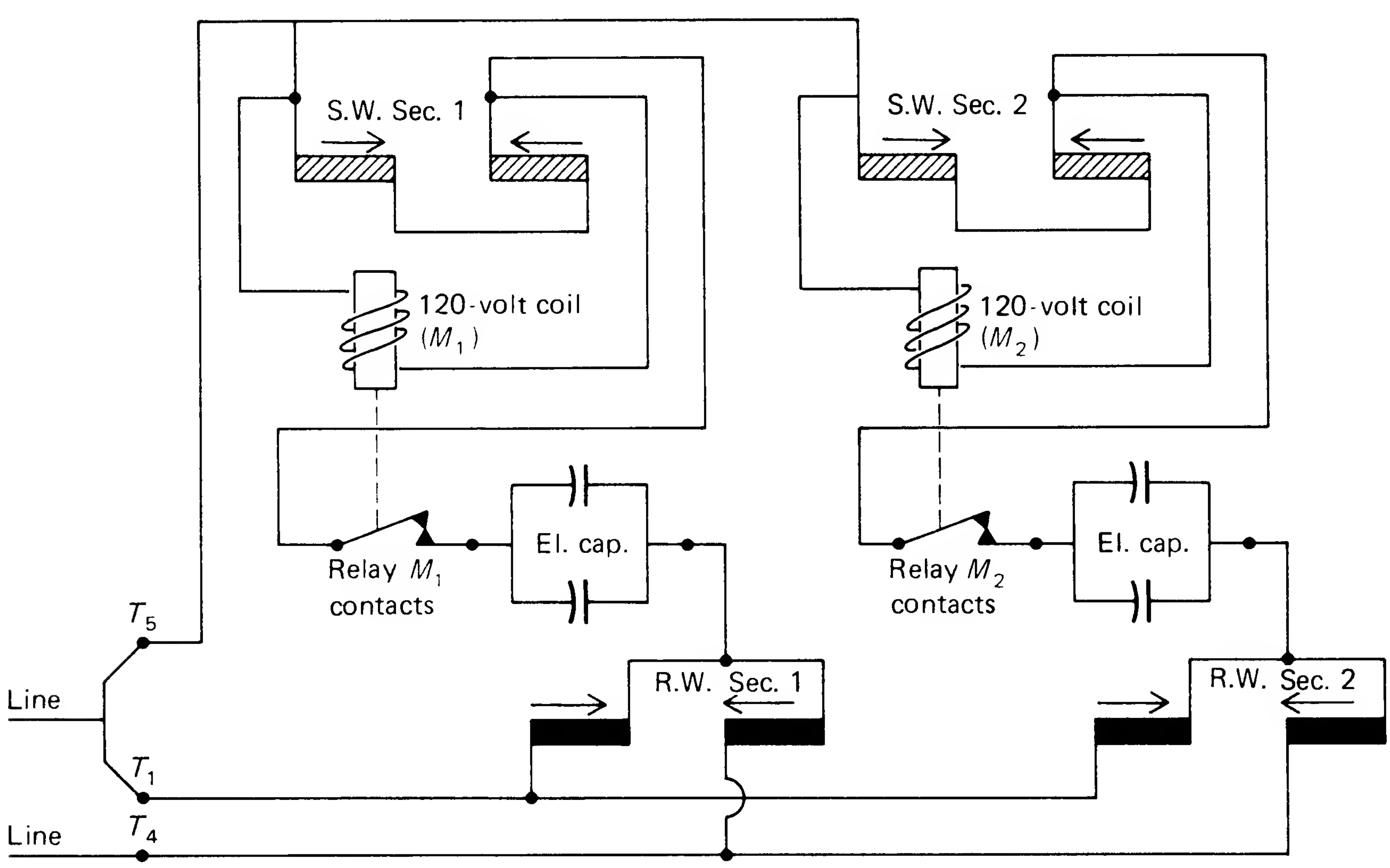


Fig. 1-151a. Straight-line diagram (a) of a large capacitor-start motor using two low-voltage potential relays. Both the start and run windings are two circuit. The motor operates on 240 volts. To reverse, put T_5 with T_4.

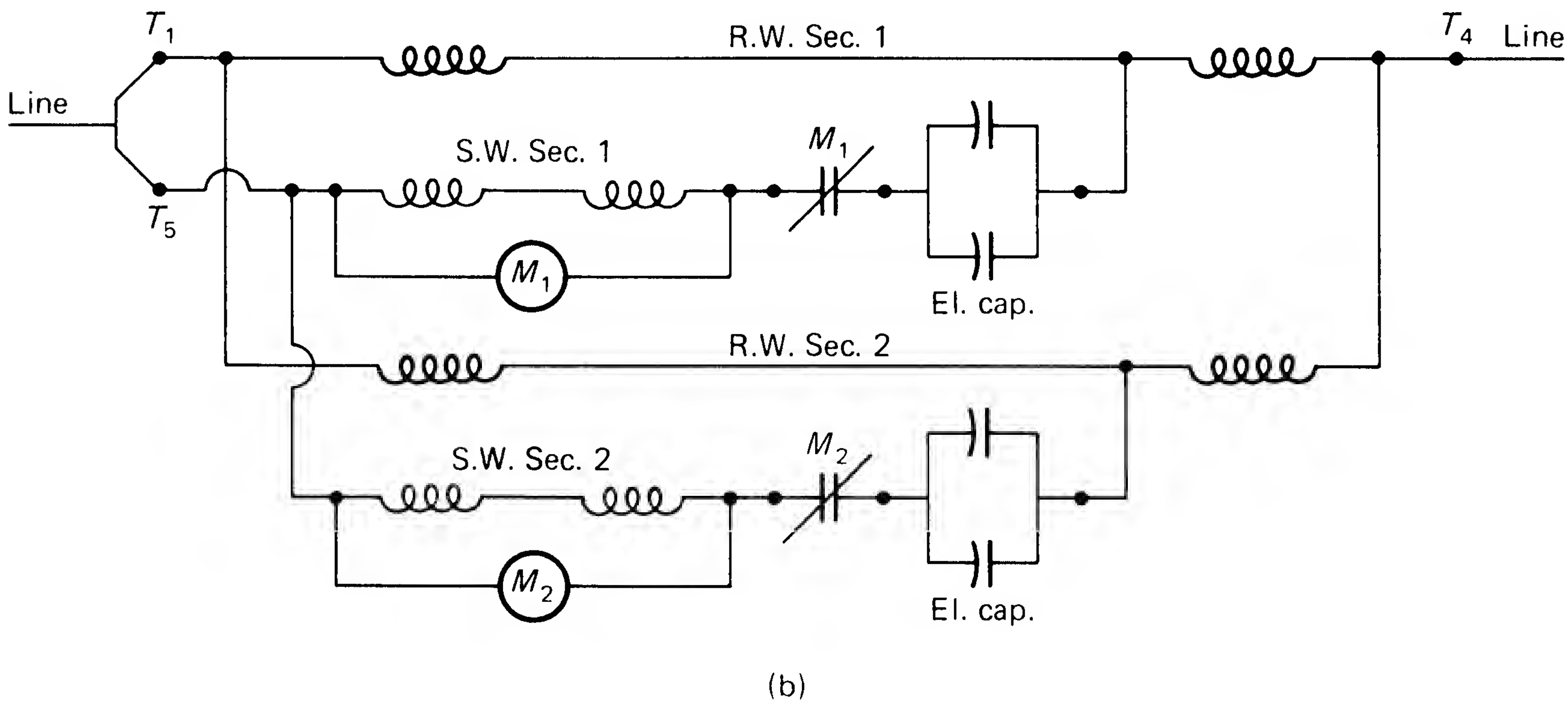
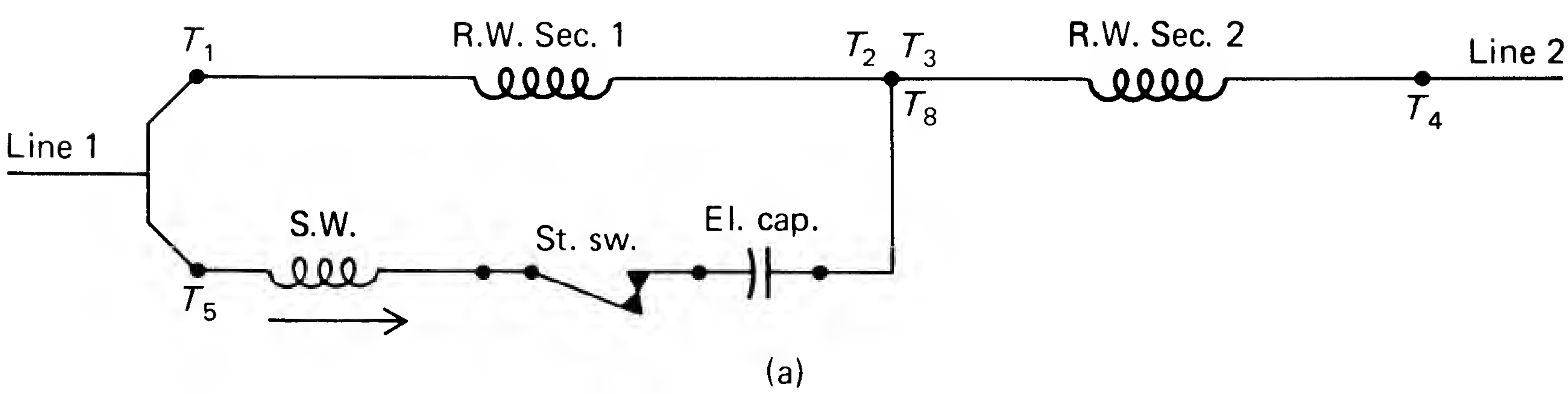


Fig. 1–151b. Schematic of (a).



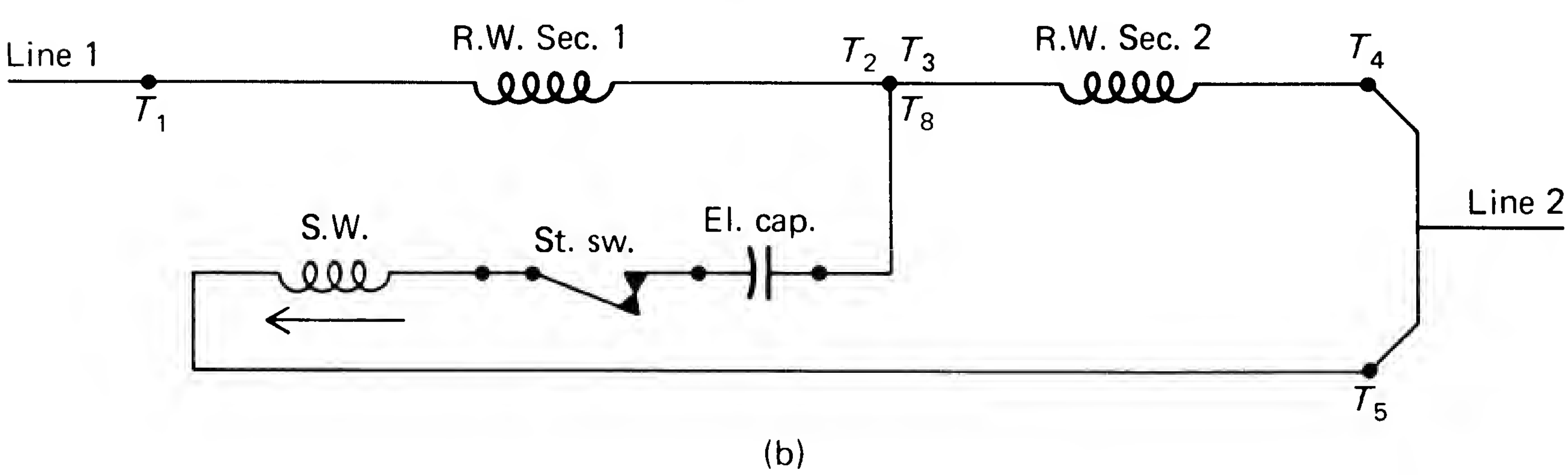


Fig. 1–152. Schematic of a dual-voltage capacitor-start motor connected for high voltage, (a) clockwise rotation facing the end opposite the shaft, and (b) counterclockwise rotation.

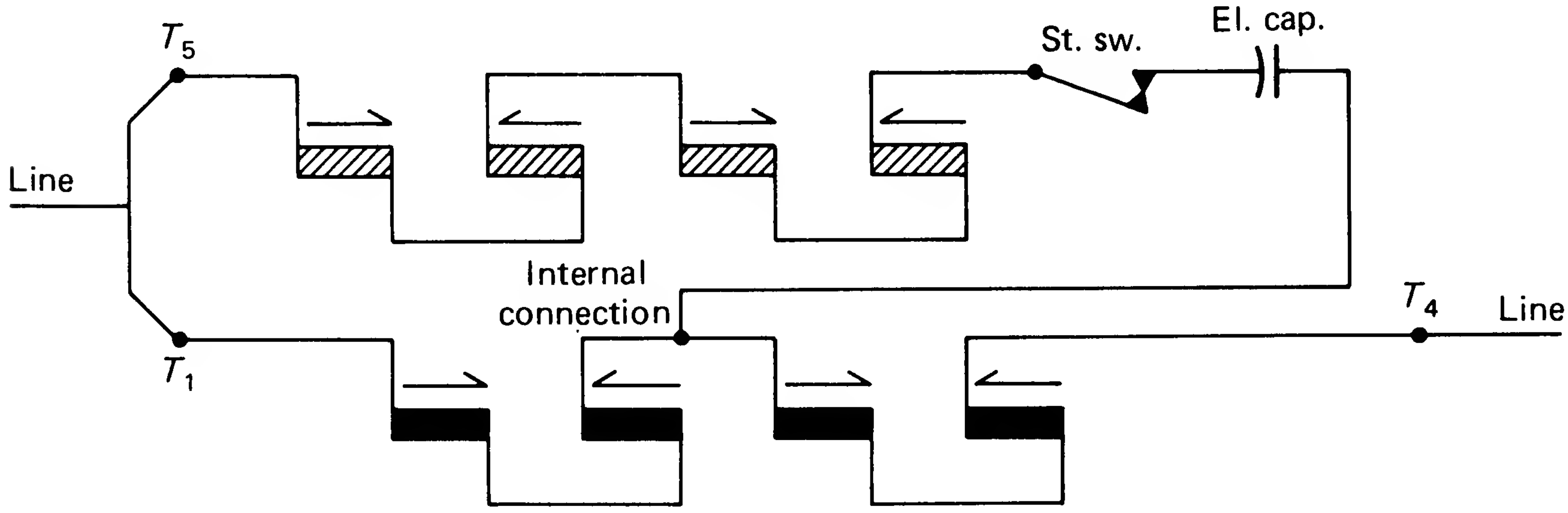


Fig. 1-153. A three-lead connection used on large capacitor-start motors. The motor is reversed by moving T_5 to T_4.

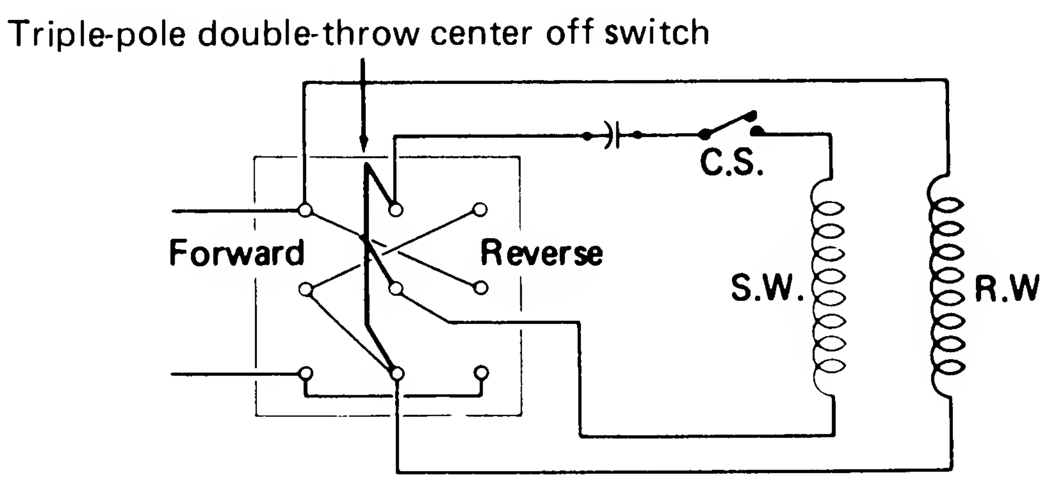


Fig. 1-154. A capacitor-start motor using a triple-pole, double throw switch for reversing.

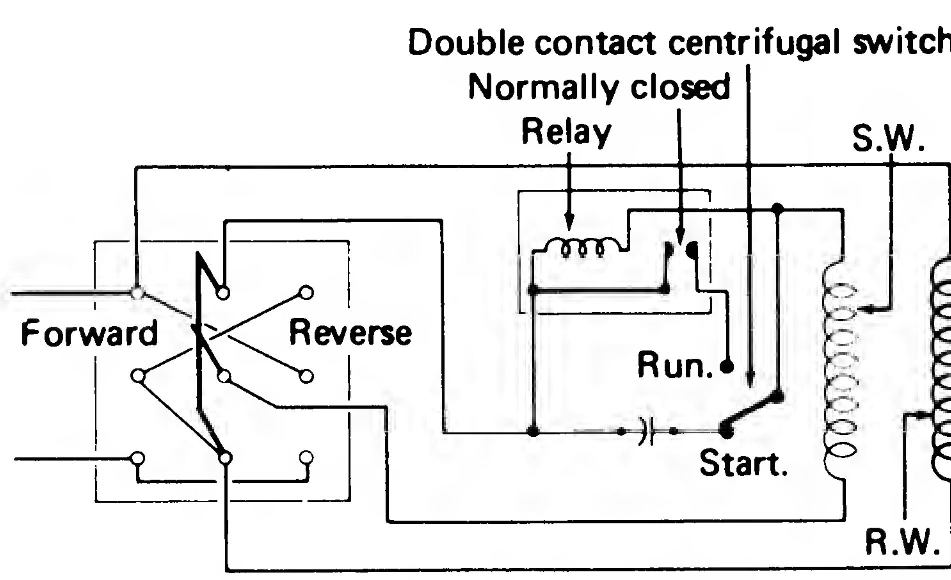


Fig. 1-155. An instantly reversible capacitor-start motor with triple-pole, double-throw switch for reversing.

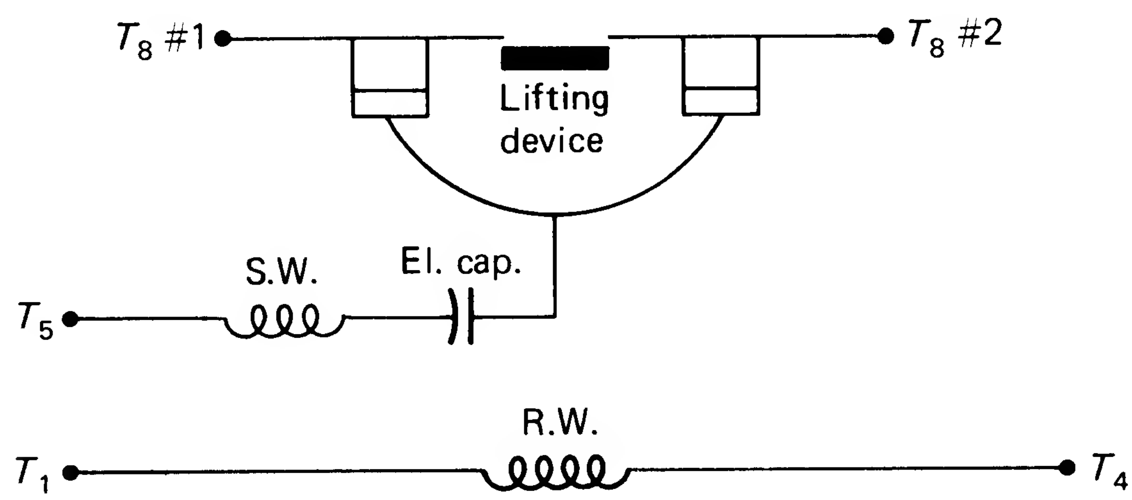


Fig. 1–156. Schematic of an instantly reversible capacitor-start motor with a stationary switch that allows instant reversal. **Figs. 1–157** and **1–58** show how it is connected in each direction.

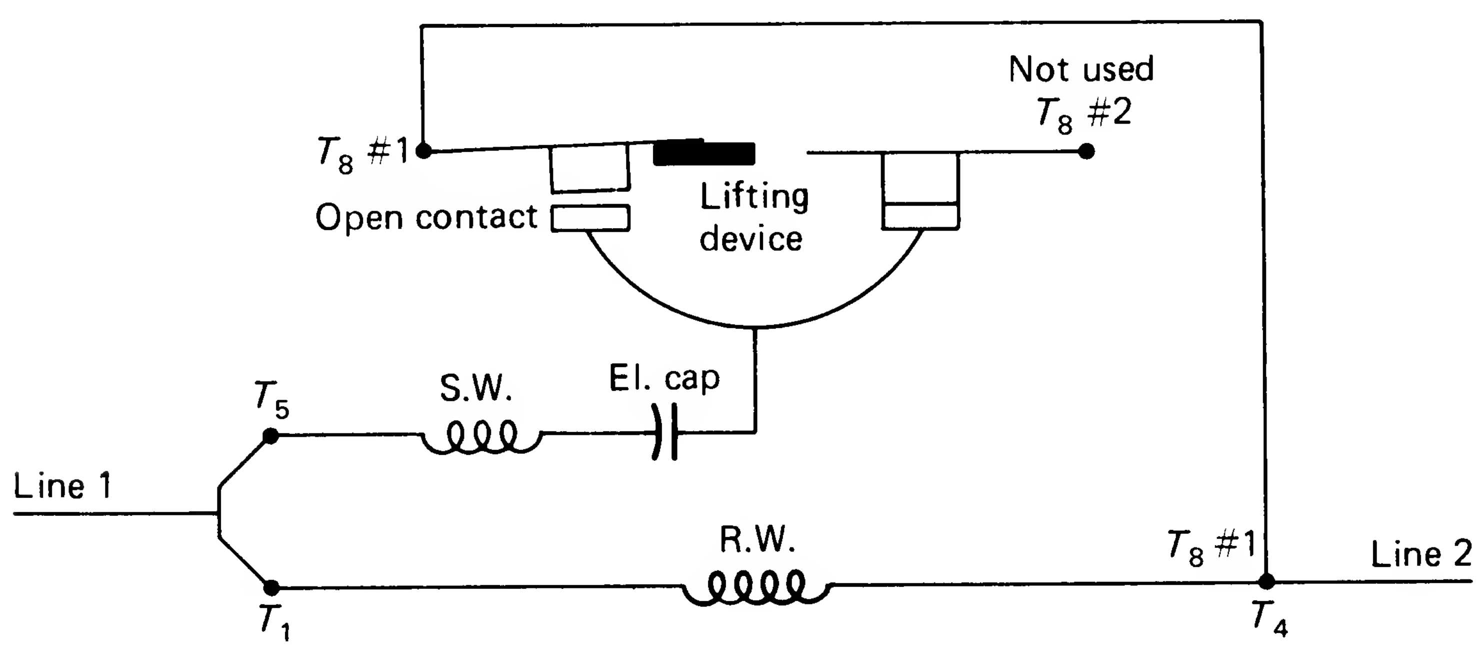


Fig. 1–157. Schematic of an instantly reversible capacitor-start motor running in a forward direction.

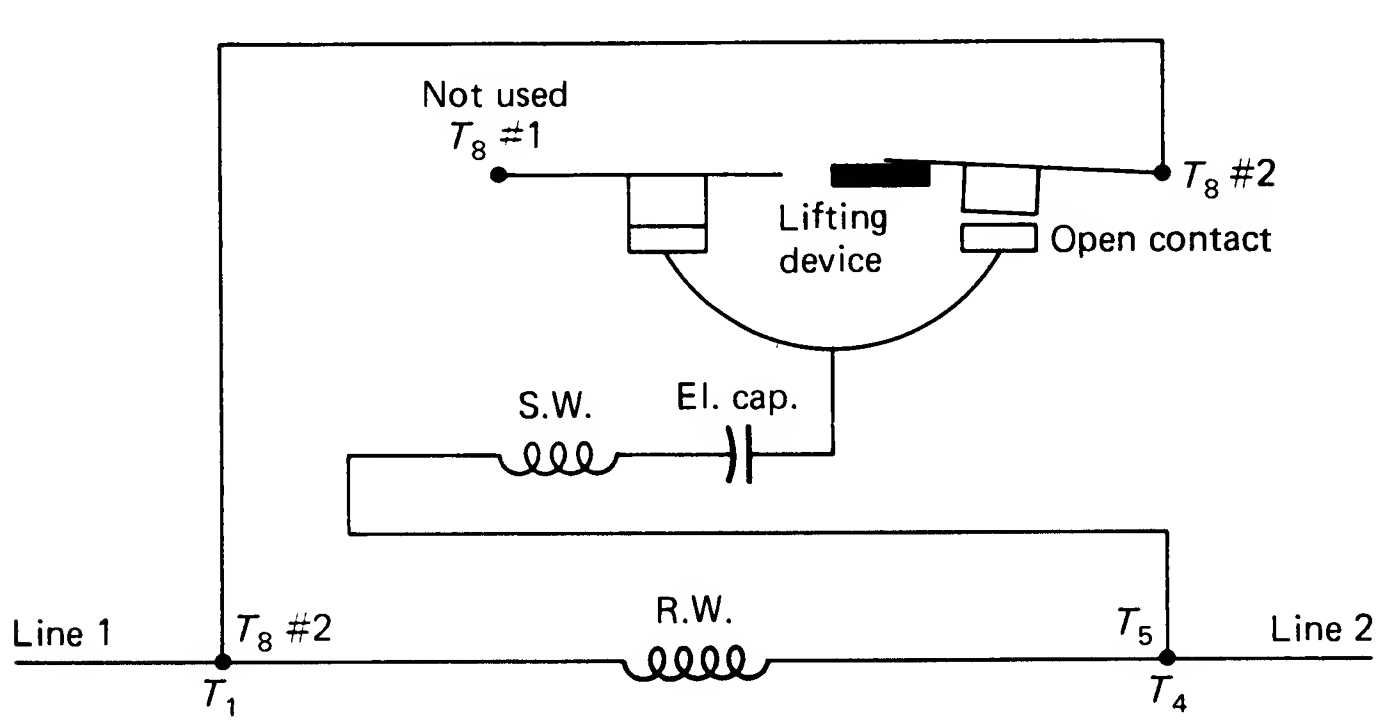


Fig. 1–158. Schematic of an instantly reversible capacitor-start motor running in reverse.

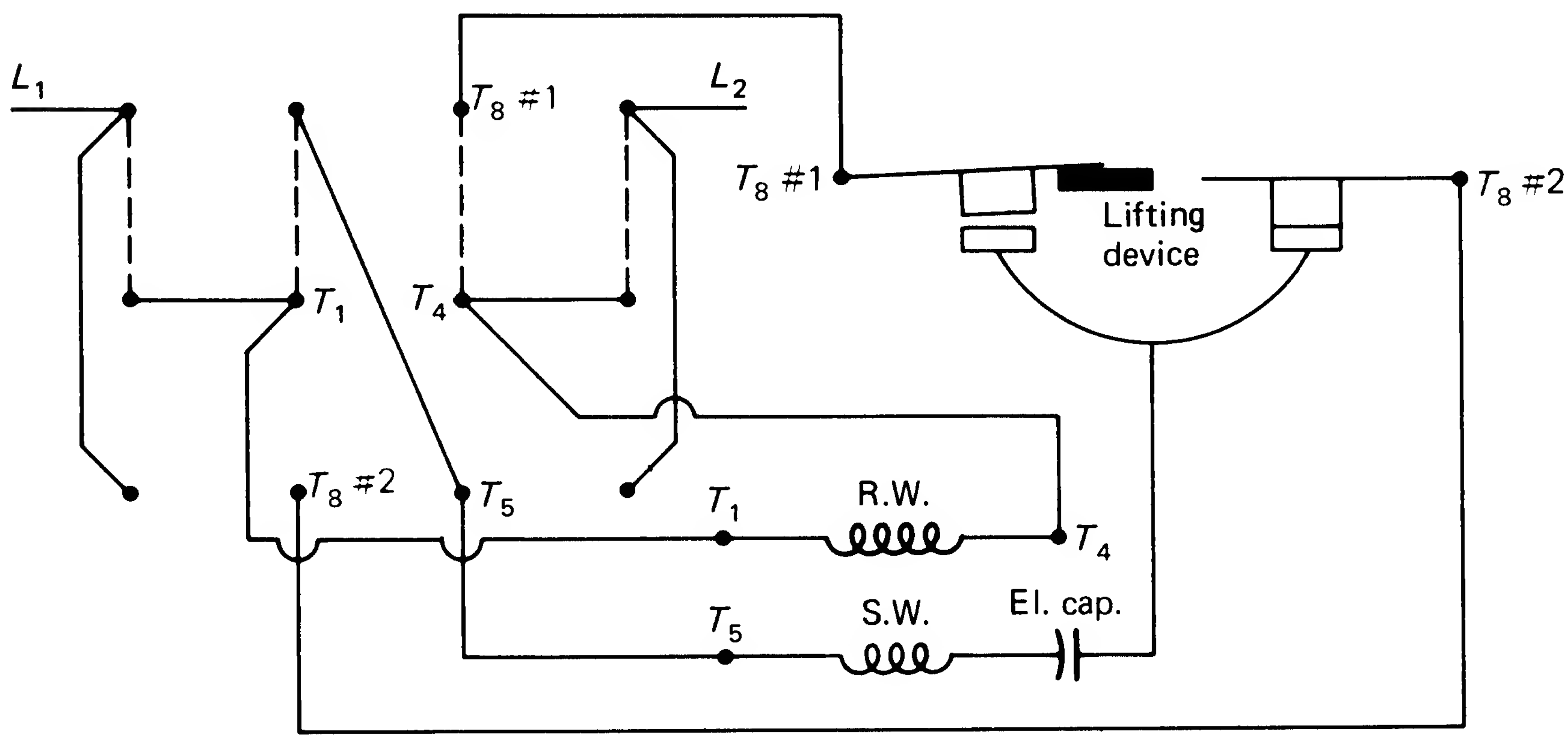


Fig. 1-159. A motor with the instant reversing stationary switch connected to a four-pole, double-throw, center-off reversing toggle switch with the switch thrown in the forward direction. Dotted lines show which terminals on the switch are joined by the switch blades in that direction.

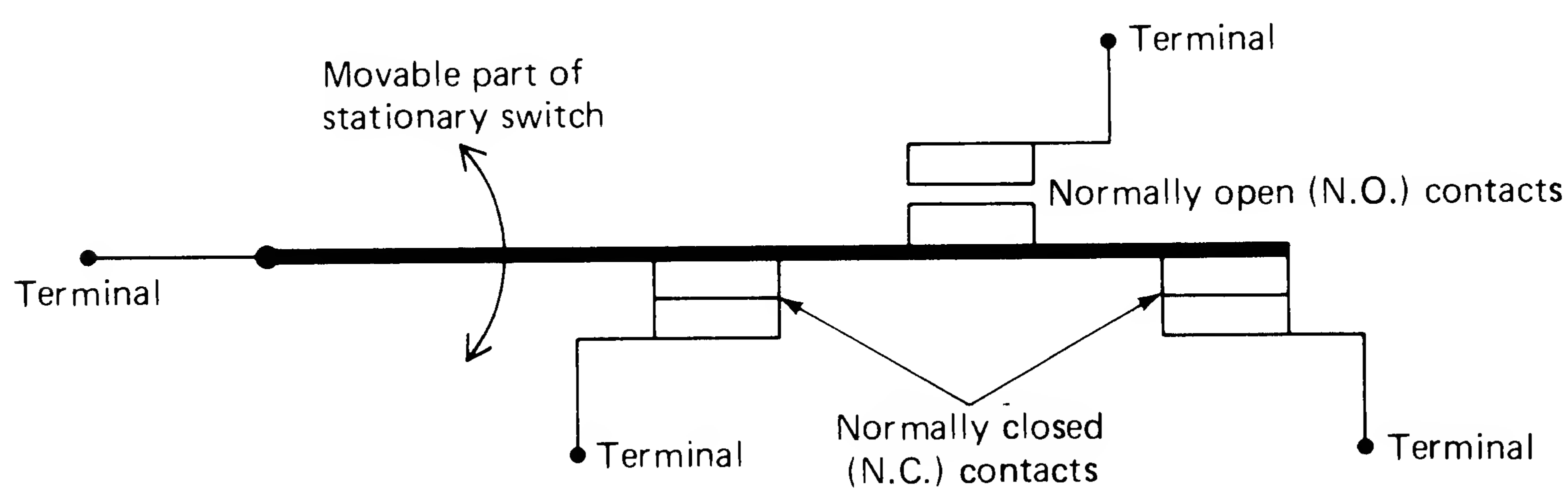


Fig. 1-160. Circuitry of the most commonly used stationary switch used in three-winding, two-speed motors (one-start winding and two-run windings).

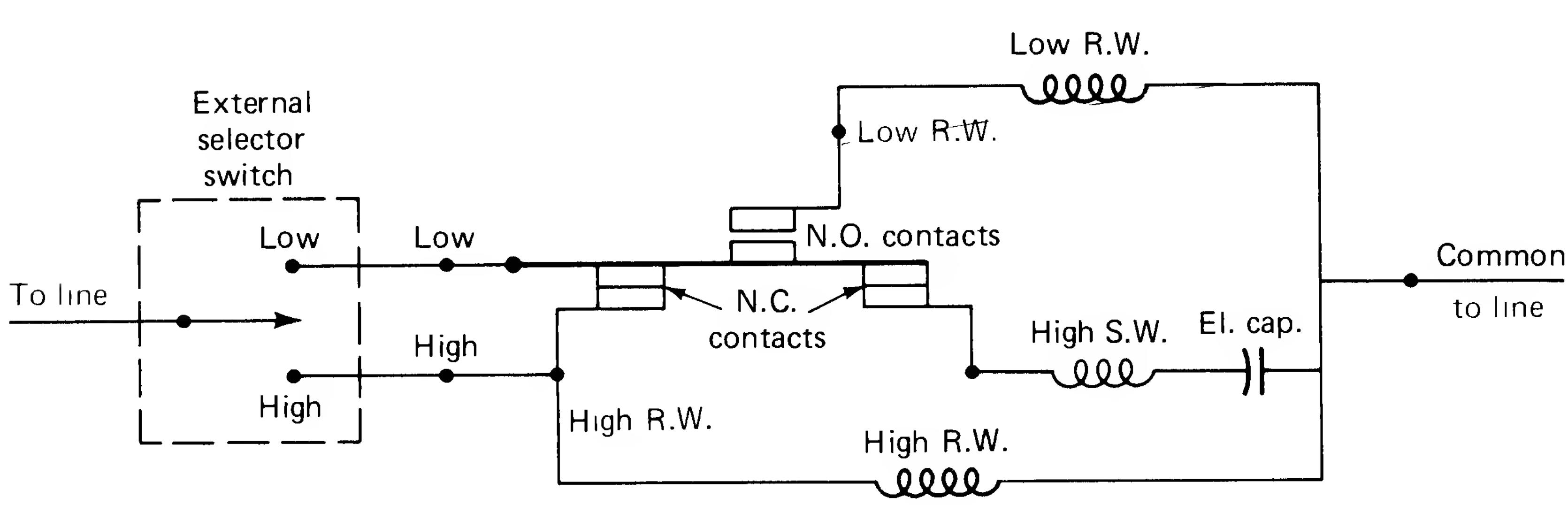


Fig. 1-161. Schematic of the external selector switch, the stationary switch contacts, and the windings as they are connected.

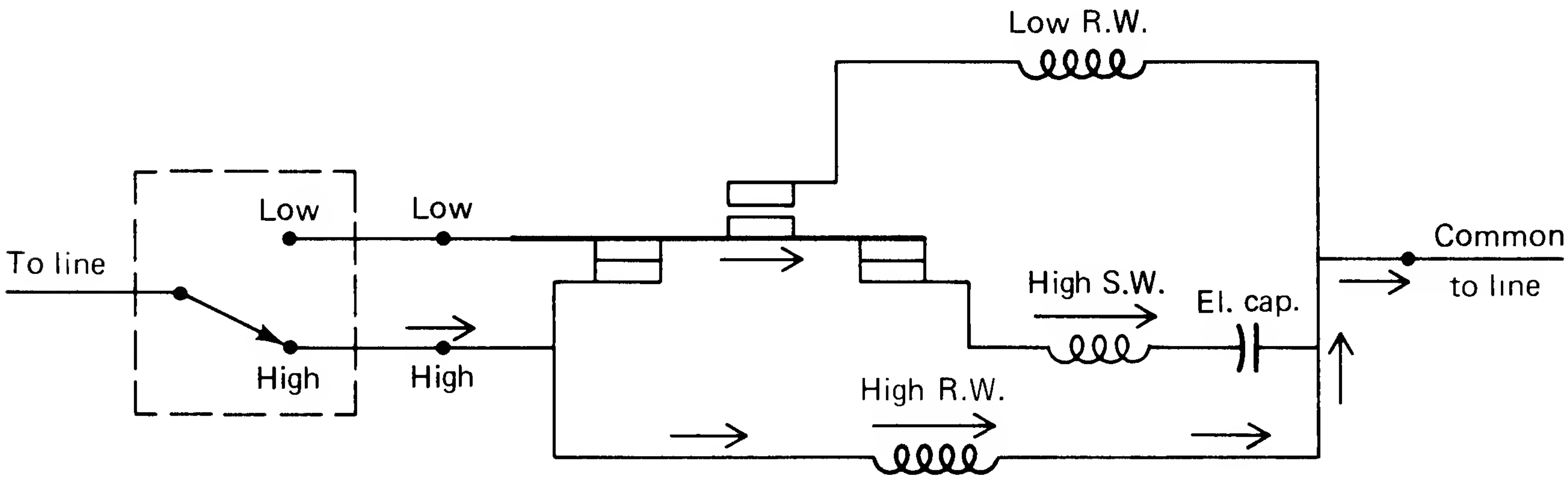


Fig. 1-162a. Two-speed capacitor-start motor schematic showing the current flow when it is starting at high speed.

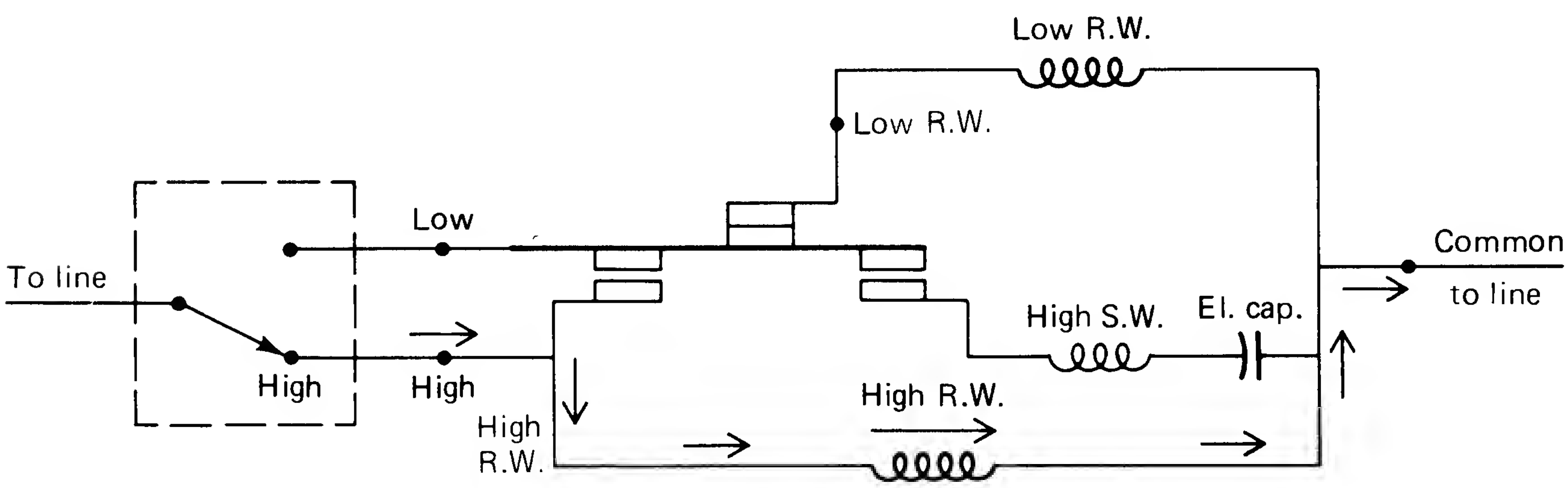


Fig. 1-162b. Two-speed capacitor-start motor schematic showing the current flow when it is running at high speed.

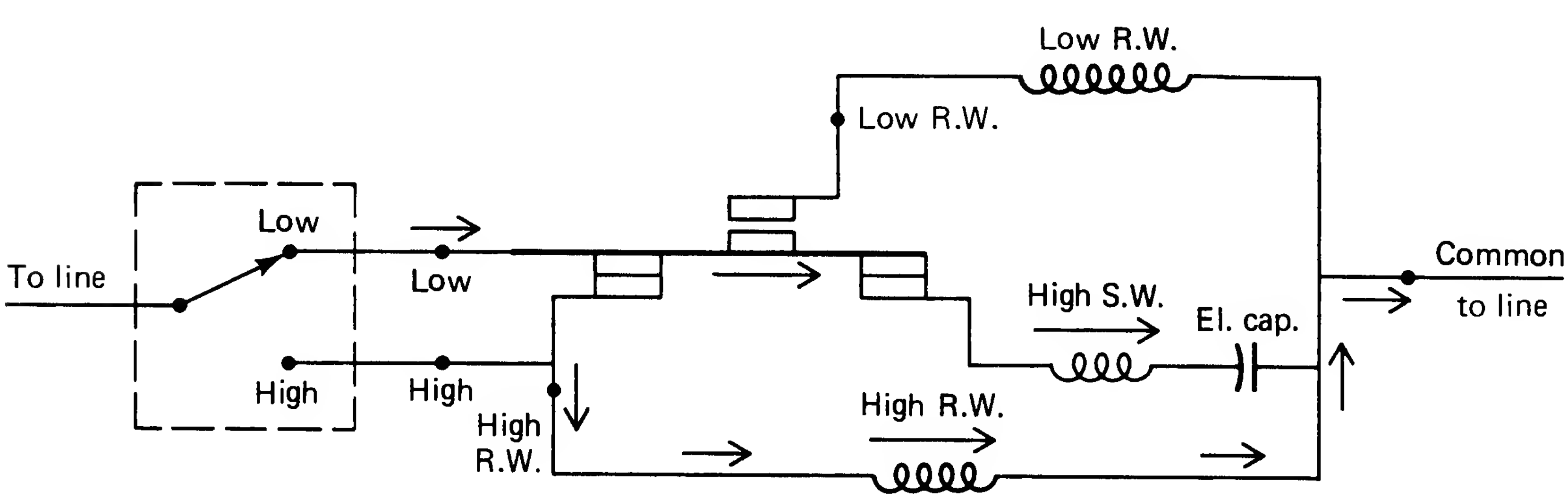


Fig. 1-163a. Two-speed capacitor-start motor schematic showing the current flow when the motor is started in low speed.

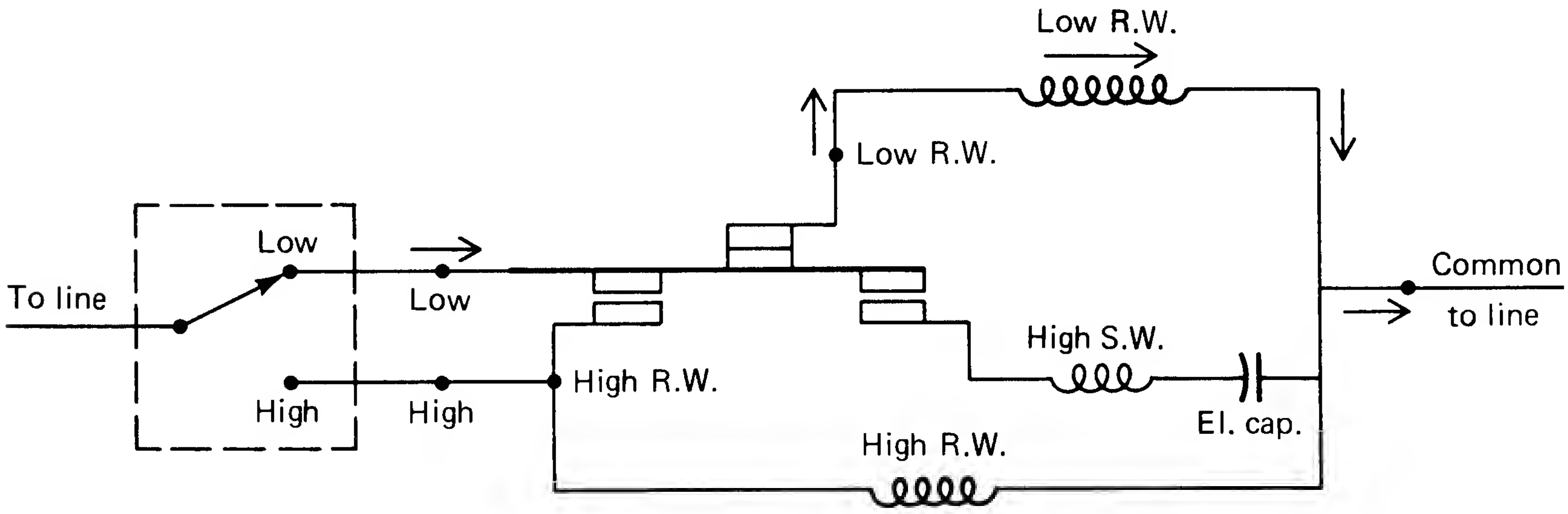


Fig. 1–163b. Two-speed capacitor-start motor schematic showing the current flow when the motor is running at low speed.

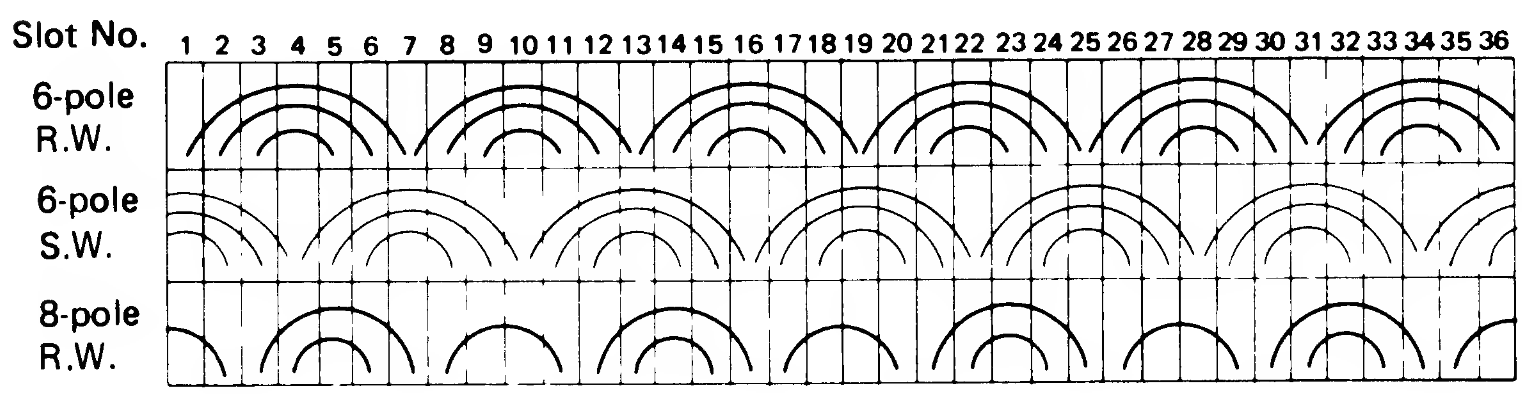


Fig. 1–163c. A typical layout of coils in a two-speed capacitor-start motor.

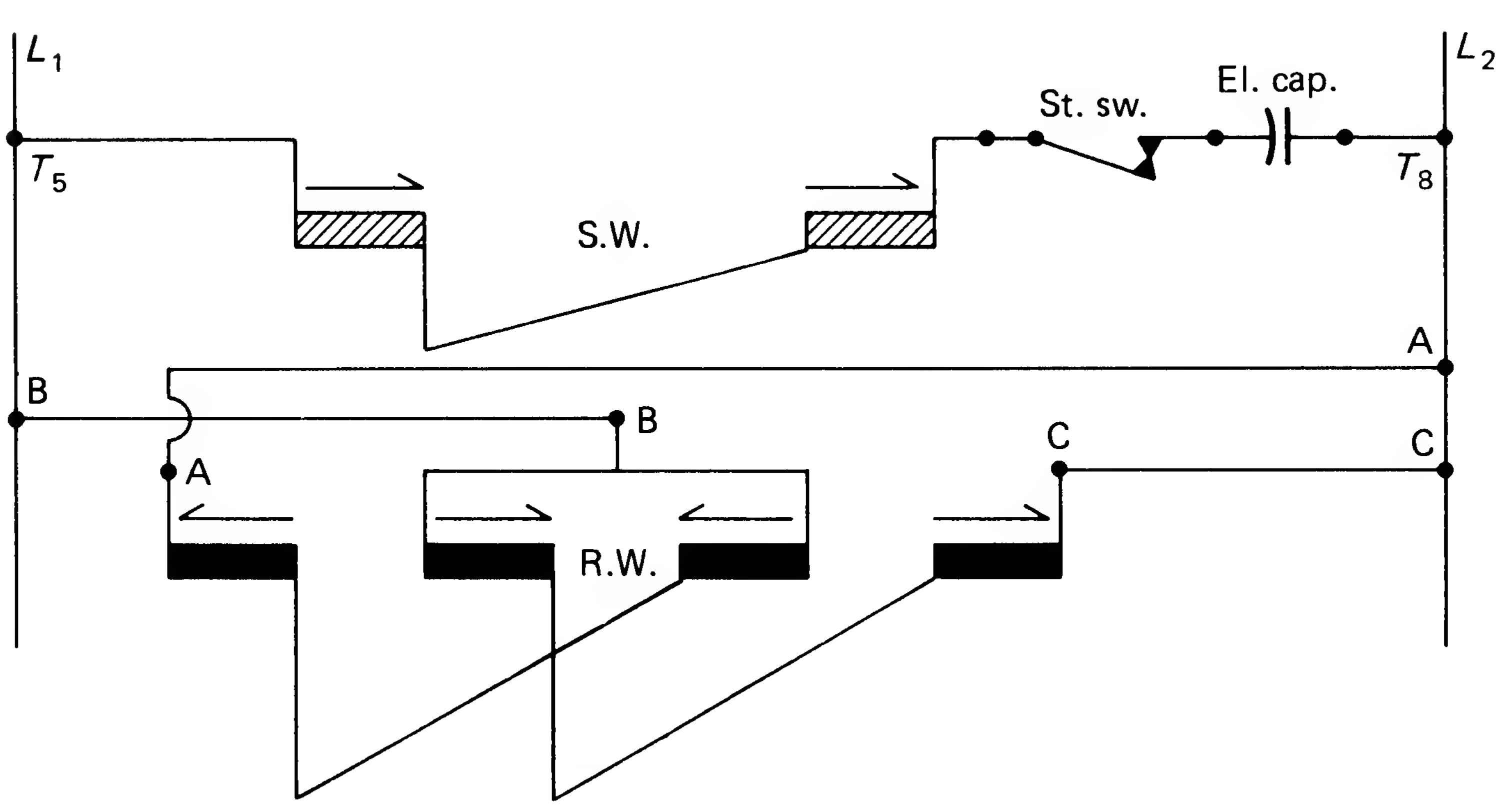


Fig. 1–164. Straight-line diagram of four- and eight-pole consequent-pole motor, connected for high speed.

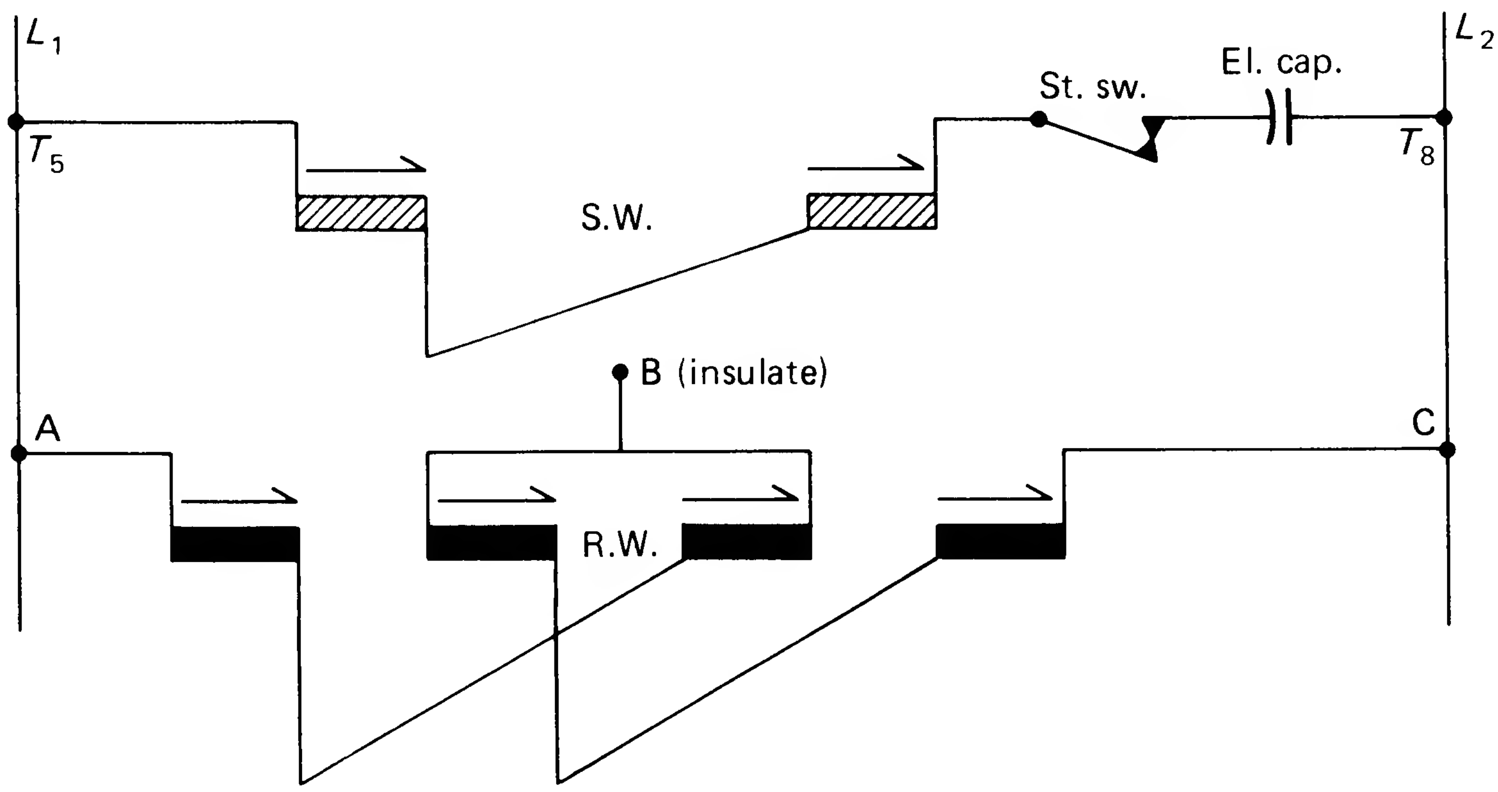


Fig. 1-165. Straight-line diagram of a four- and eight-pole consequent-pole motor connected for low speed.

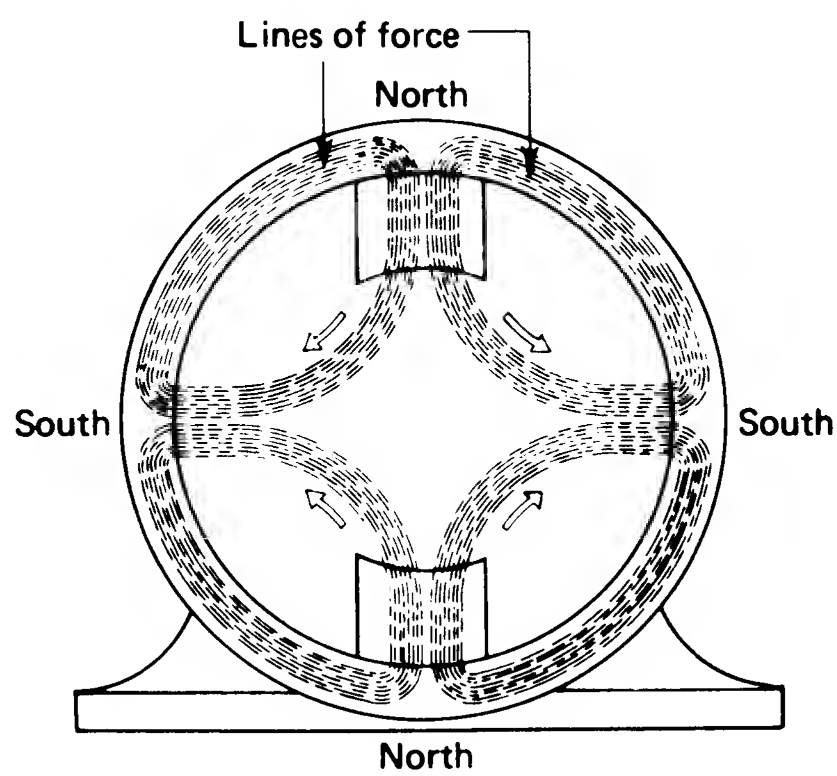


Fig. 1-166. If the two poles of a two-pole motor are connected so that like polarity results, two more poles will be formed by the lines of force entering the frame.

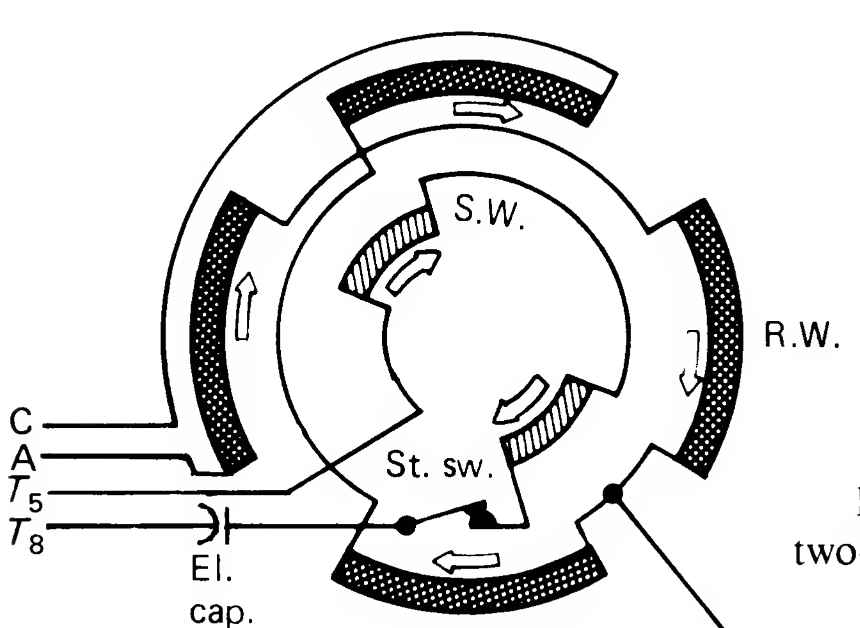


Fig. 1-167. Circular diagram of a two-speed capacitor-start motor.

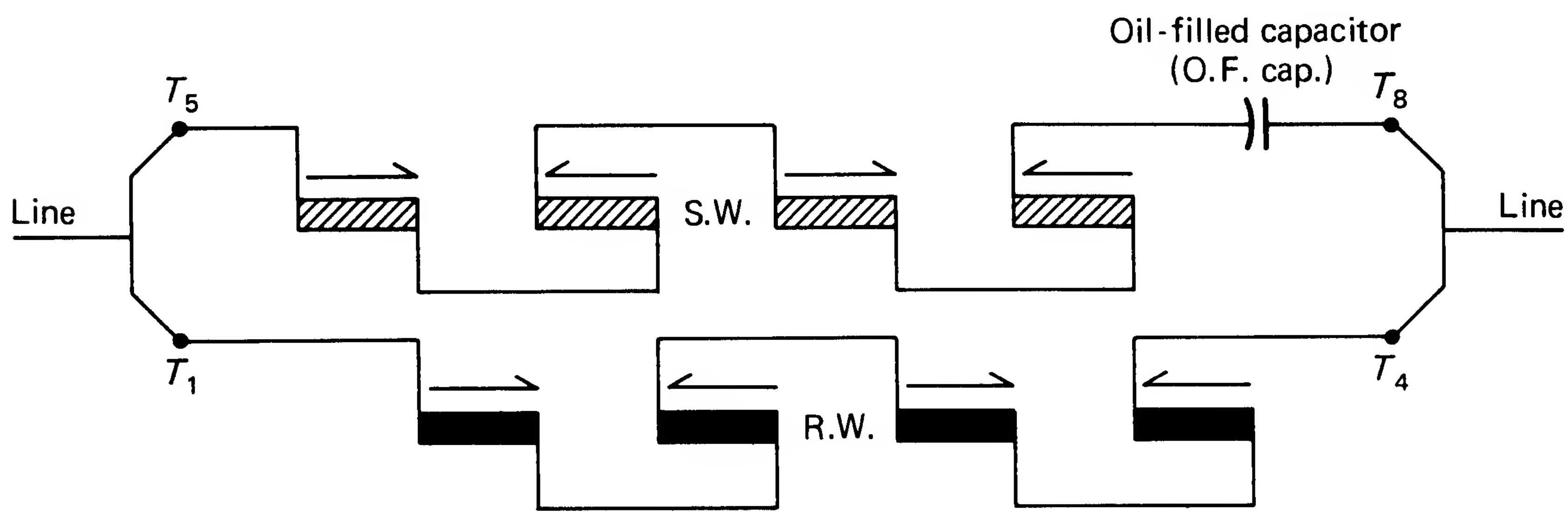


Fig. 1-168. Permanent-split, capacitor-run, reversible motor.

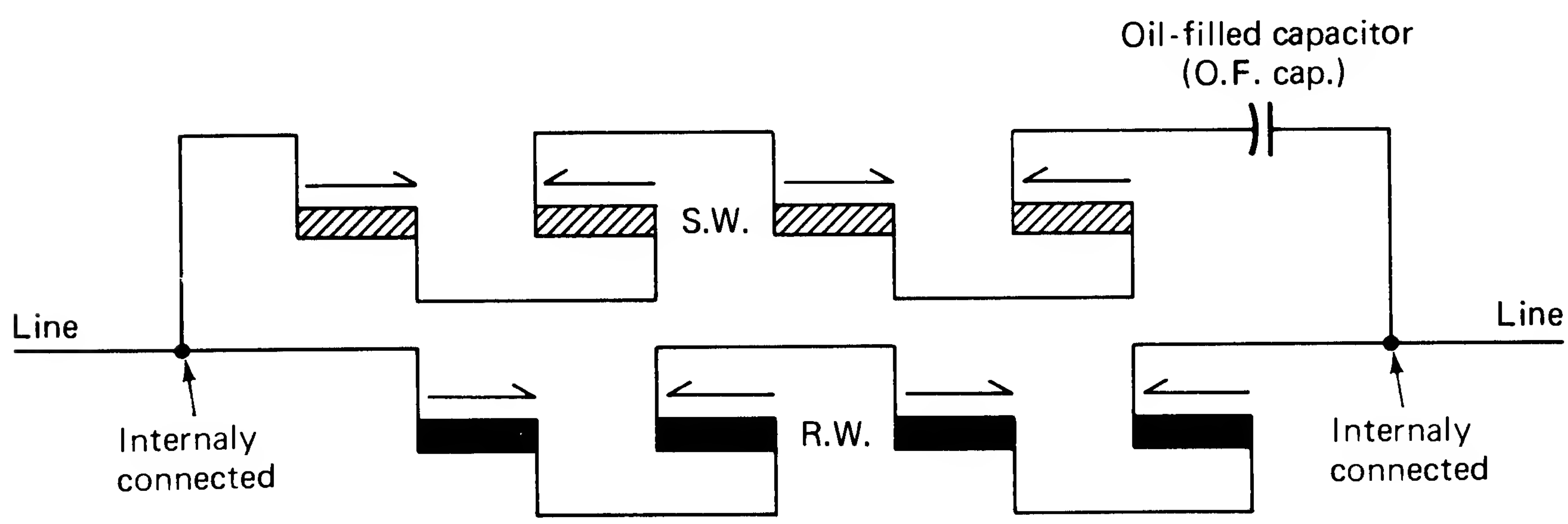


Fig. 1-169a. Permanent-split, capacitor-run, nonreversible motor.

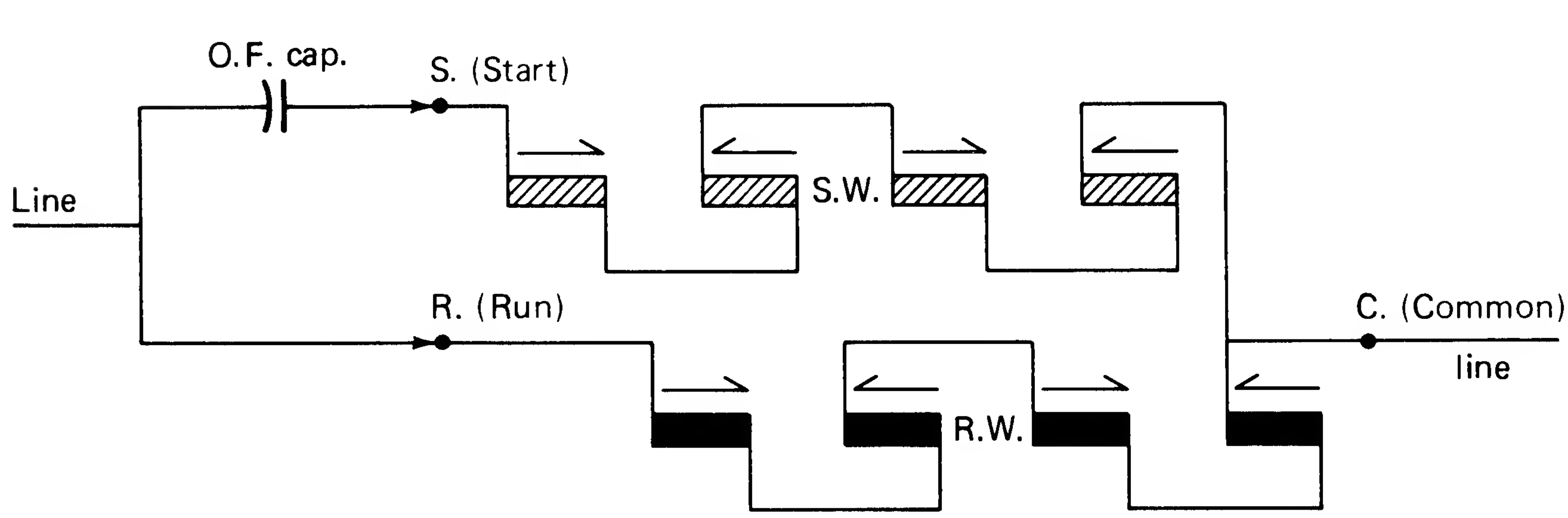


Fig. 1-169b. Straight-line diagram of a permanent-split, capacitor-run motor and the terminal markings, as found on a refrigeration compressor.

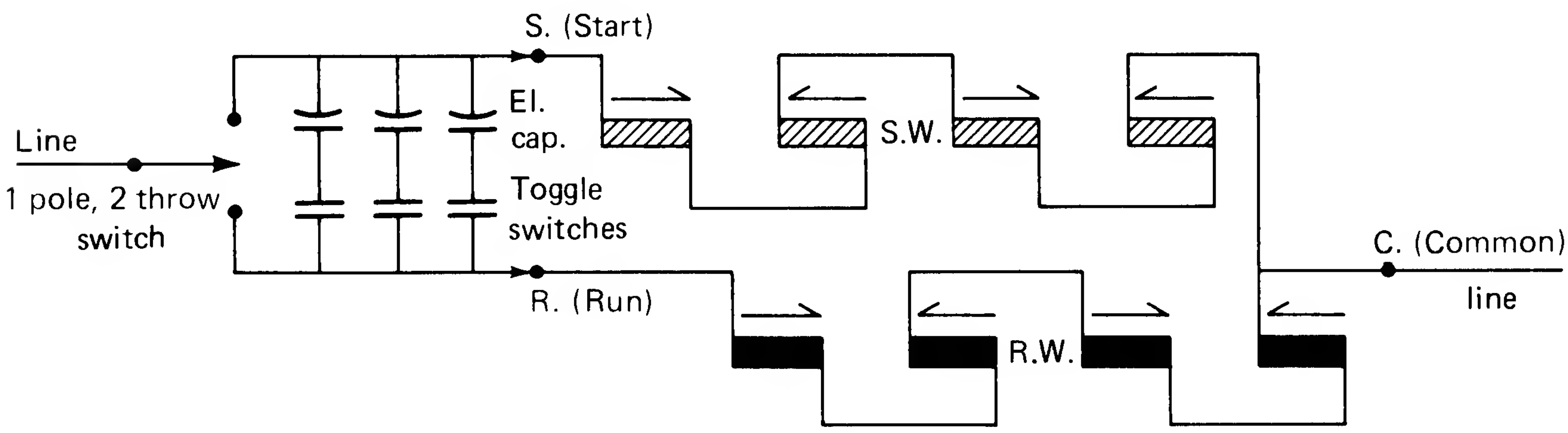


Fig. 1-170. Starting unit consisting of a single-pole, double-throw toggle switch, three electrolytic capacitors, and three toggle switches and leads connected to a refrigeration compressor motor.

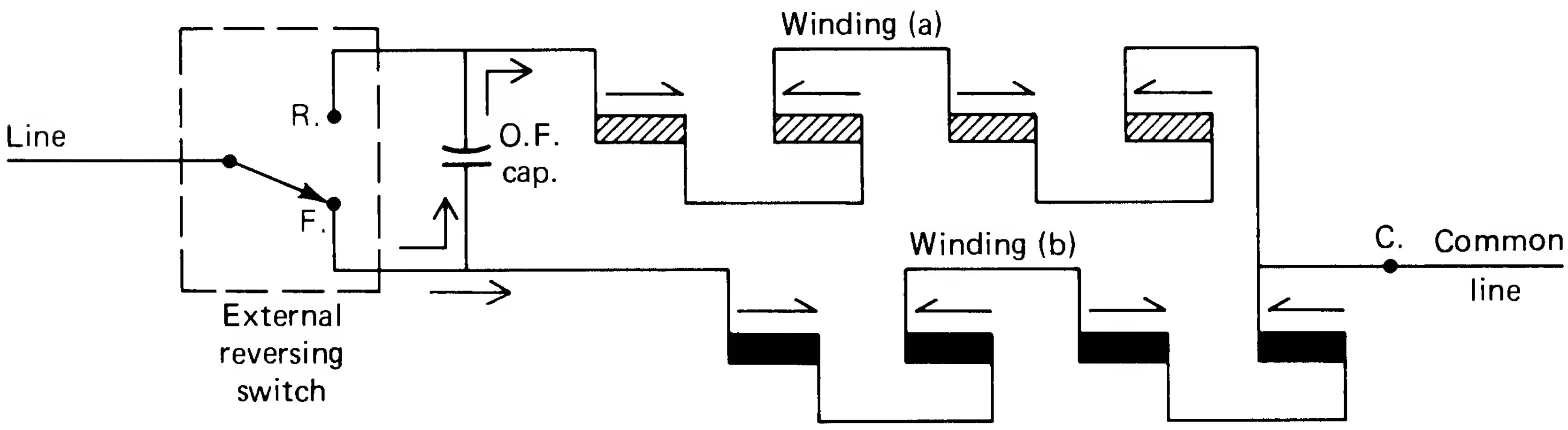


Fig. 1-171. Special-duty, permanent-split, capacitor-run motor going forward because the capacitor is in series with winding, making (a) the start winding and (b) the run winding.

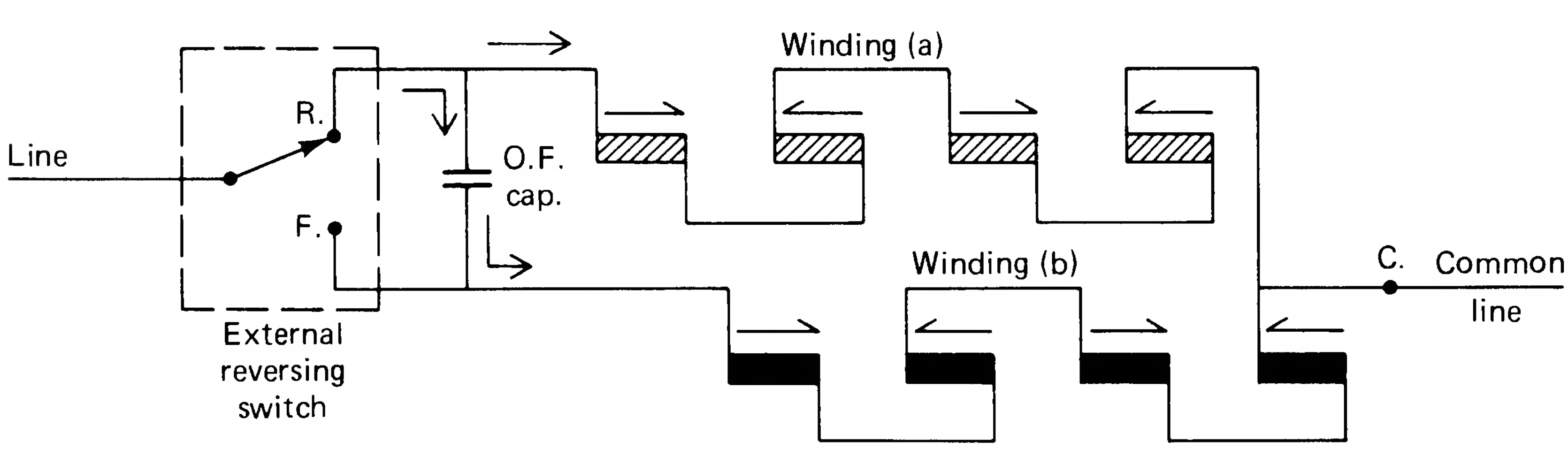


Fig. 1-172. The same motor as in **Fig. 1-171**, with the capacitor in series with the winding (b). This makes (b) the start winding and (a) the run winding, and the motor will run in reverse.

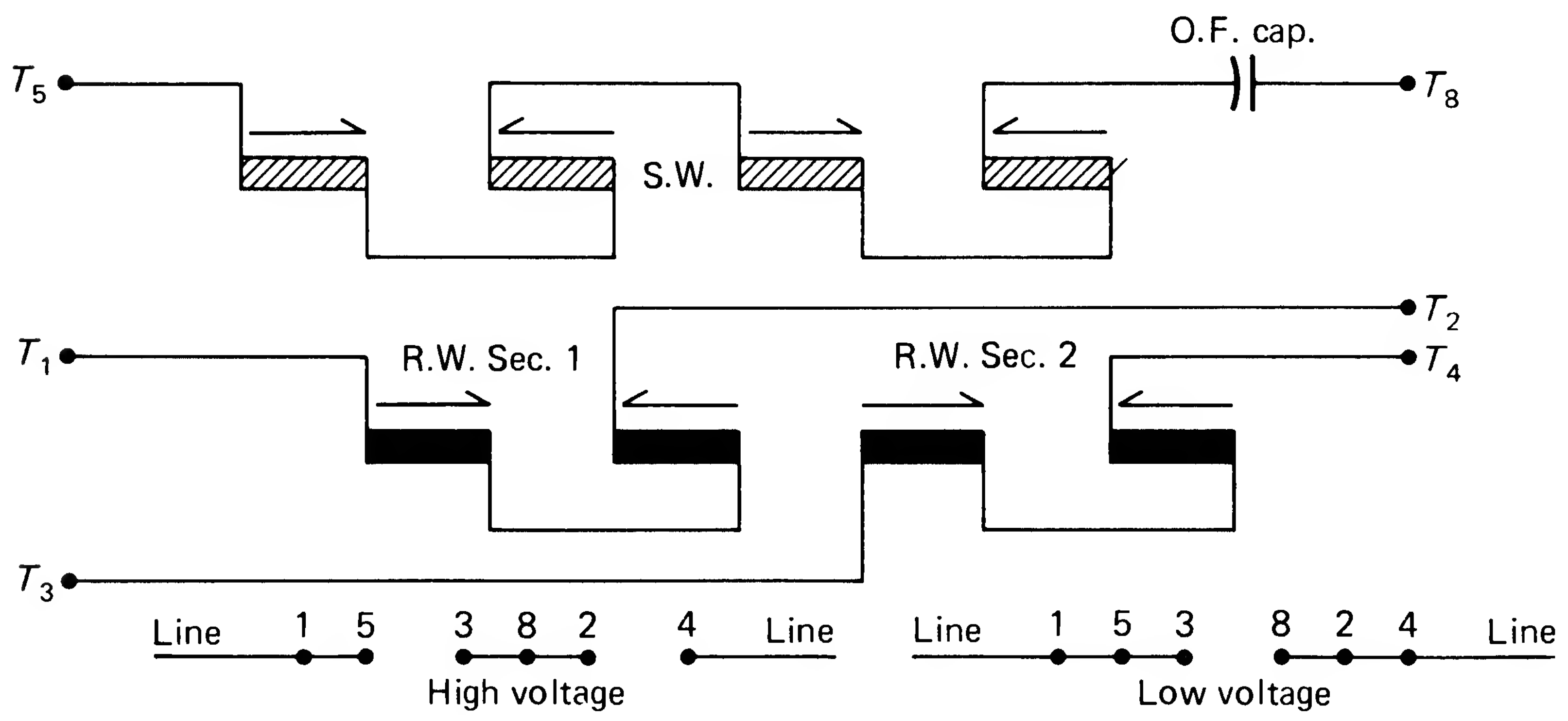


Fig. 1-173. Two-voltage permanent-split, capacitor-run motor connected short jumper.

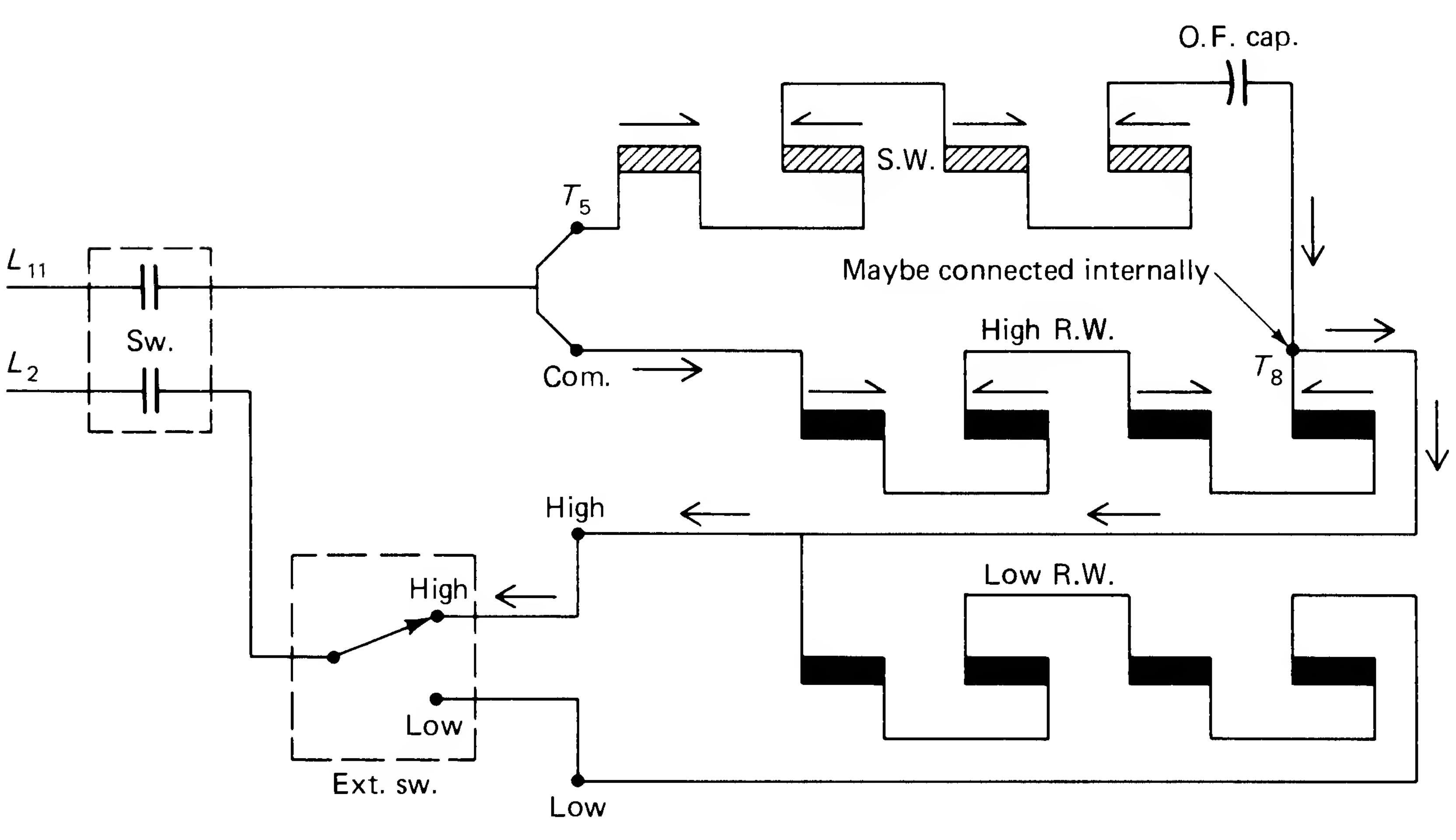


Fig. 1-174a. Two-speed permanent-split, capacitor-run motor connected for high speed. The low-speed winding is idle on high speed.

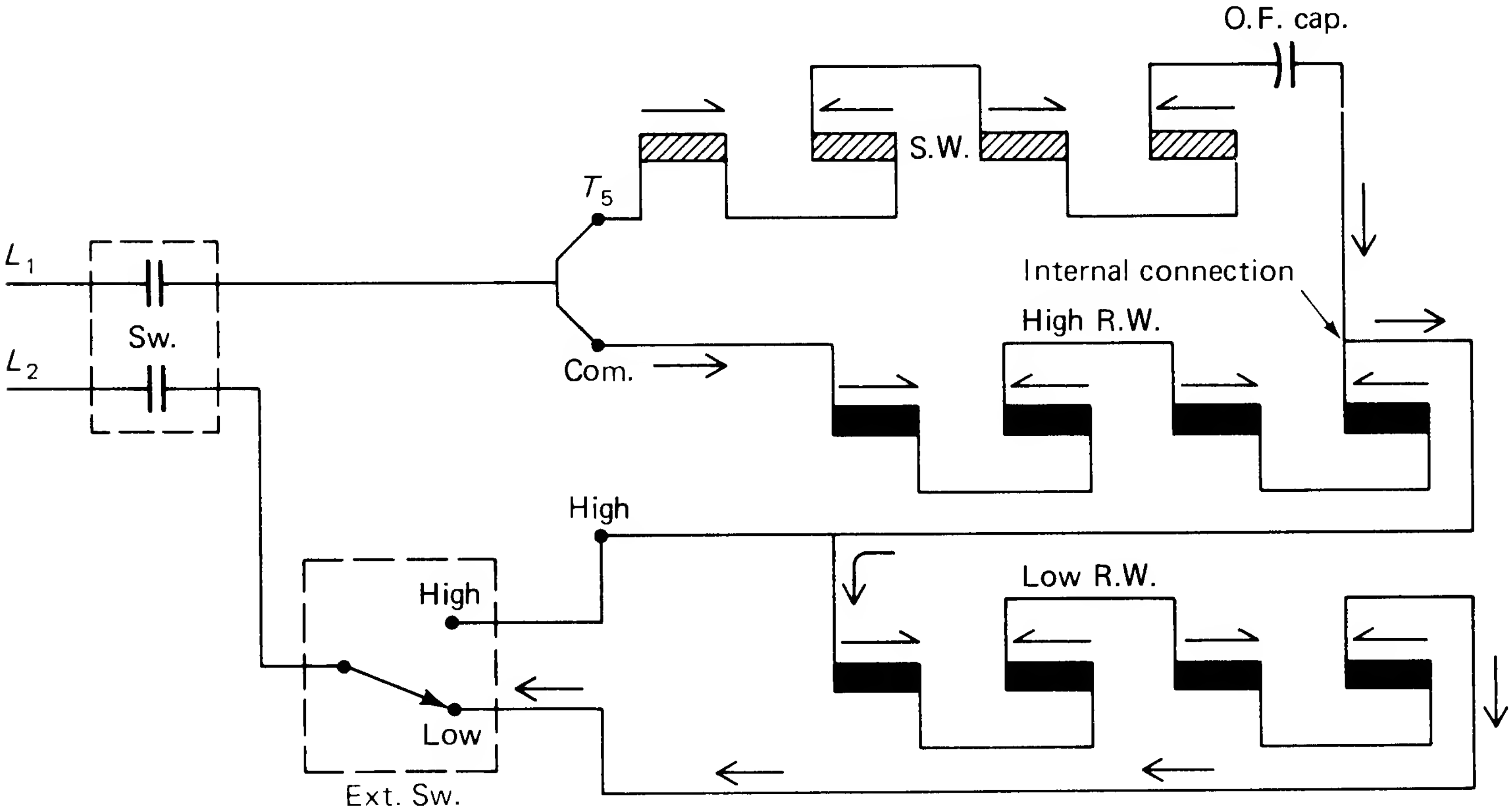


Fig. 1-174b. Two-speed permanent-split capacitor-run motor connected for low speed. Both the high- and low-speed windings are energized in series.

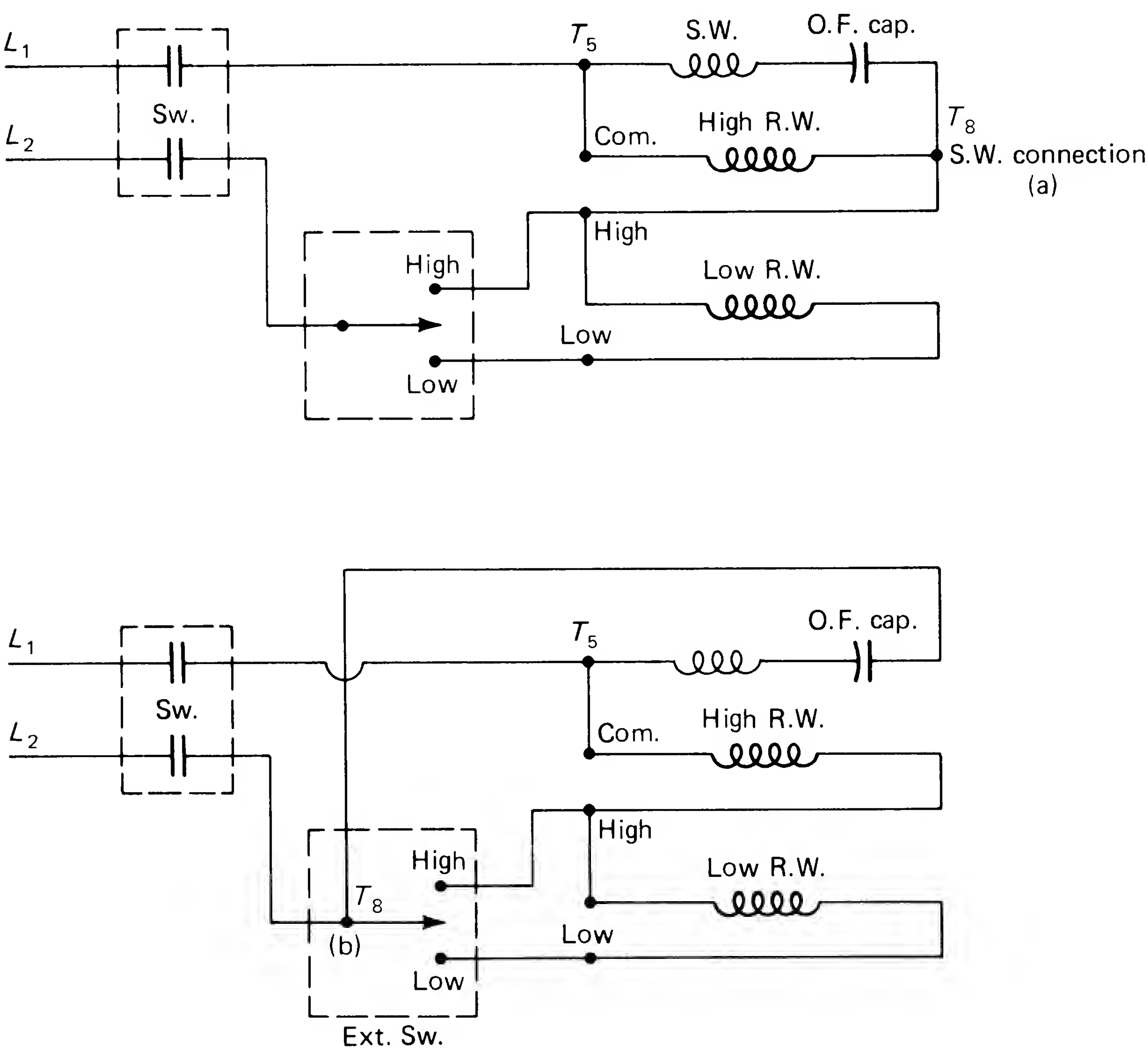


Fig. 1-175. Schematics showing the two start-winding connections used in a multispeed, permanent-split, capacitor-run motor. Connection (a) is across the high run winding, and connection (b) is across the line.

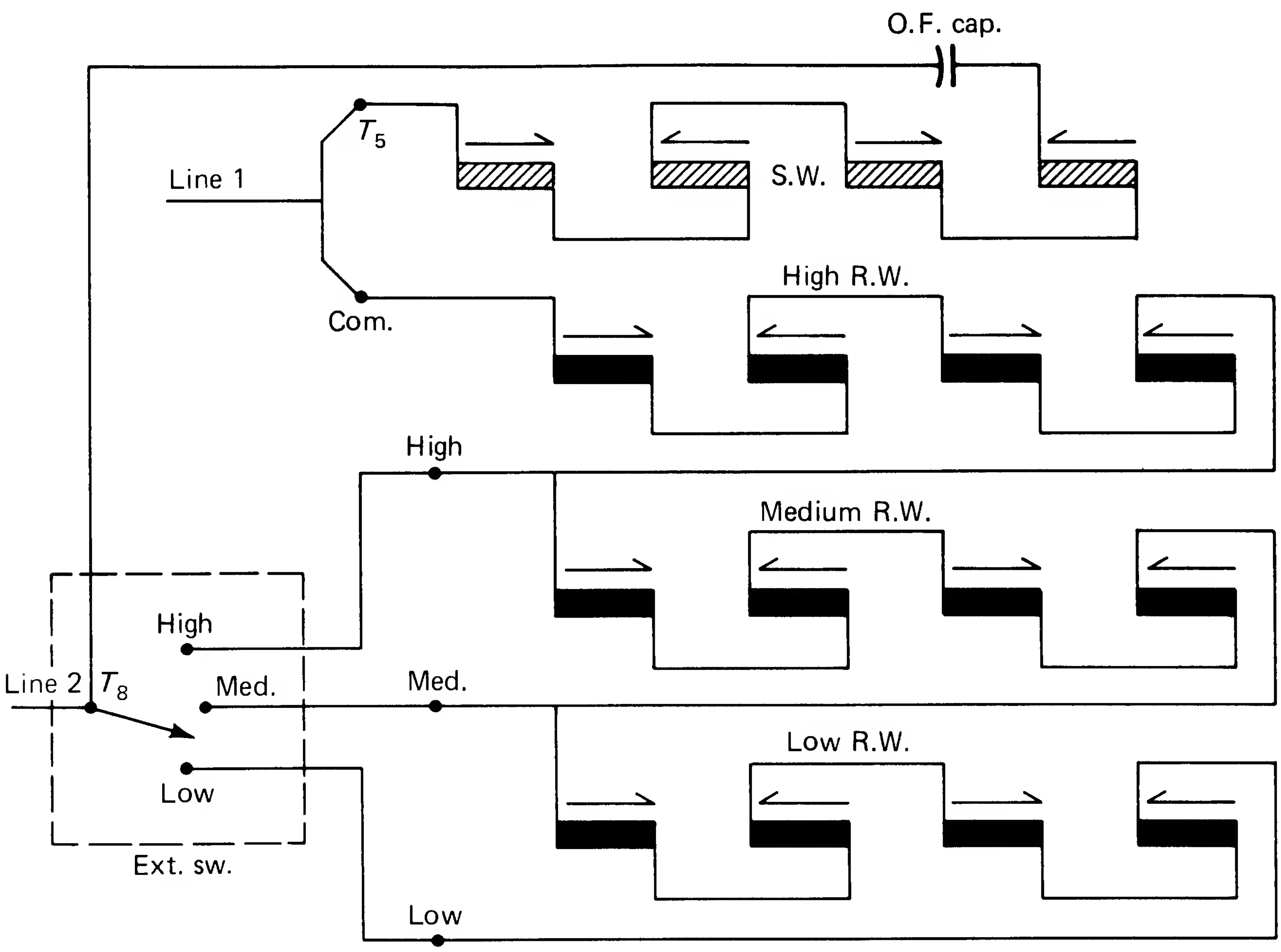


Fig. 1–176. Three-speed permanent-split, capacitor-run motor and external selector switch.

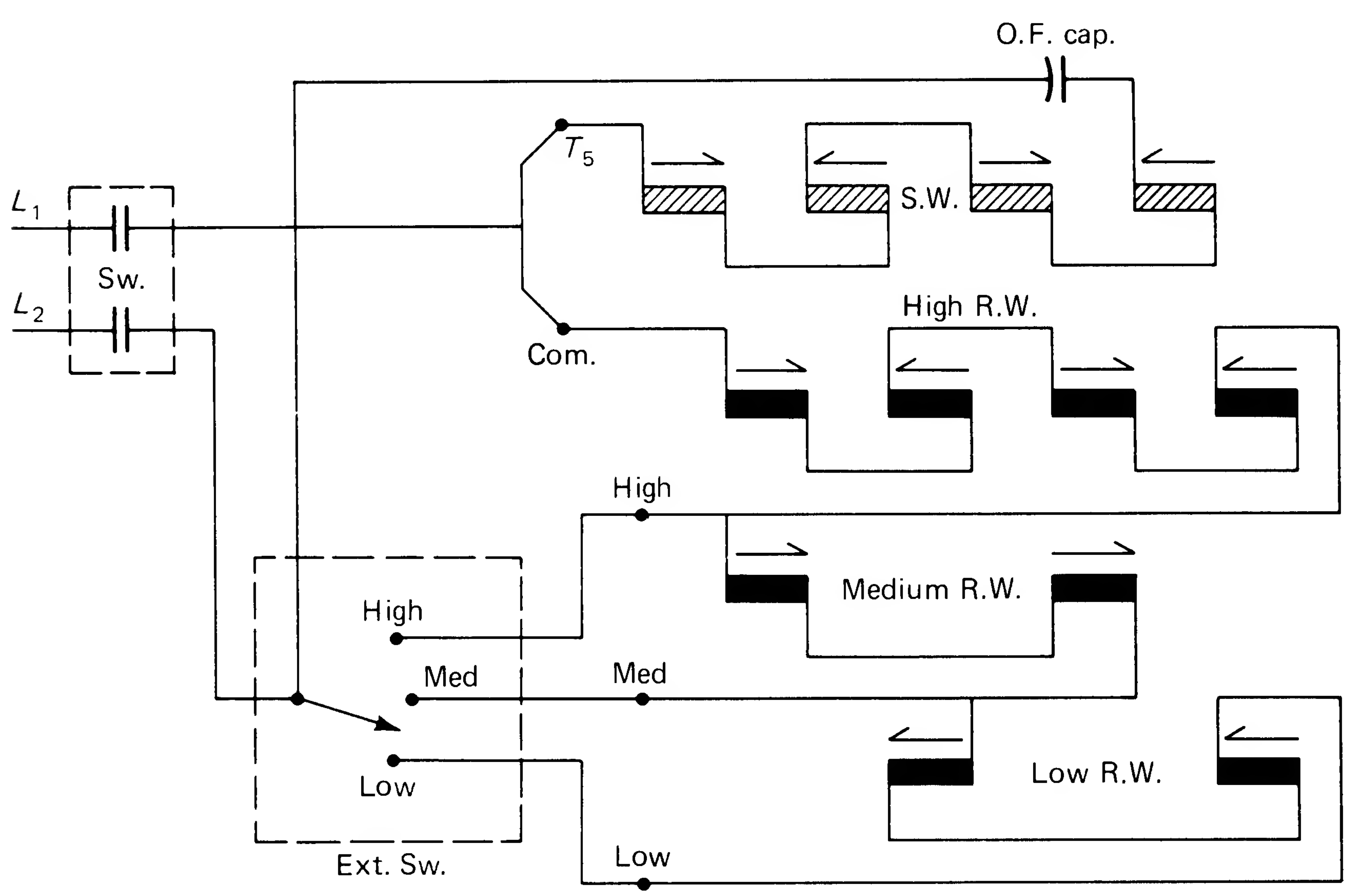


Fig. 1–177. Three-speed permanent-split, capacitor-run motor and external selector switch.

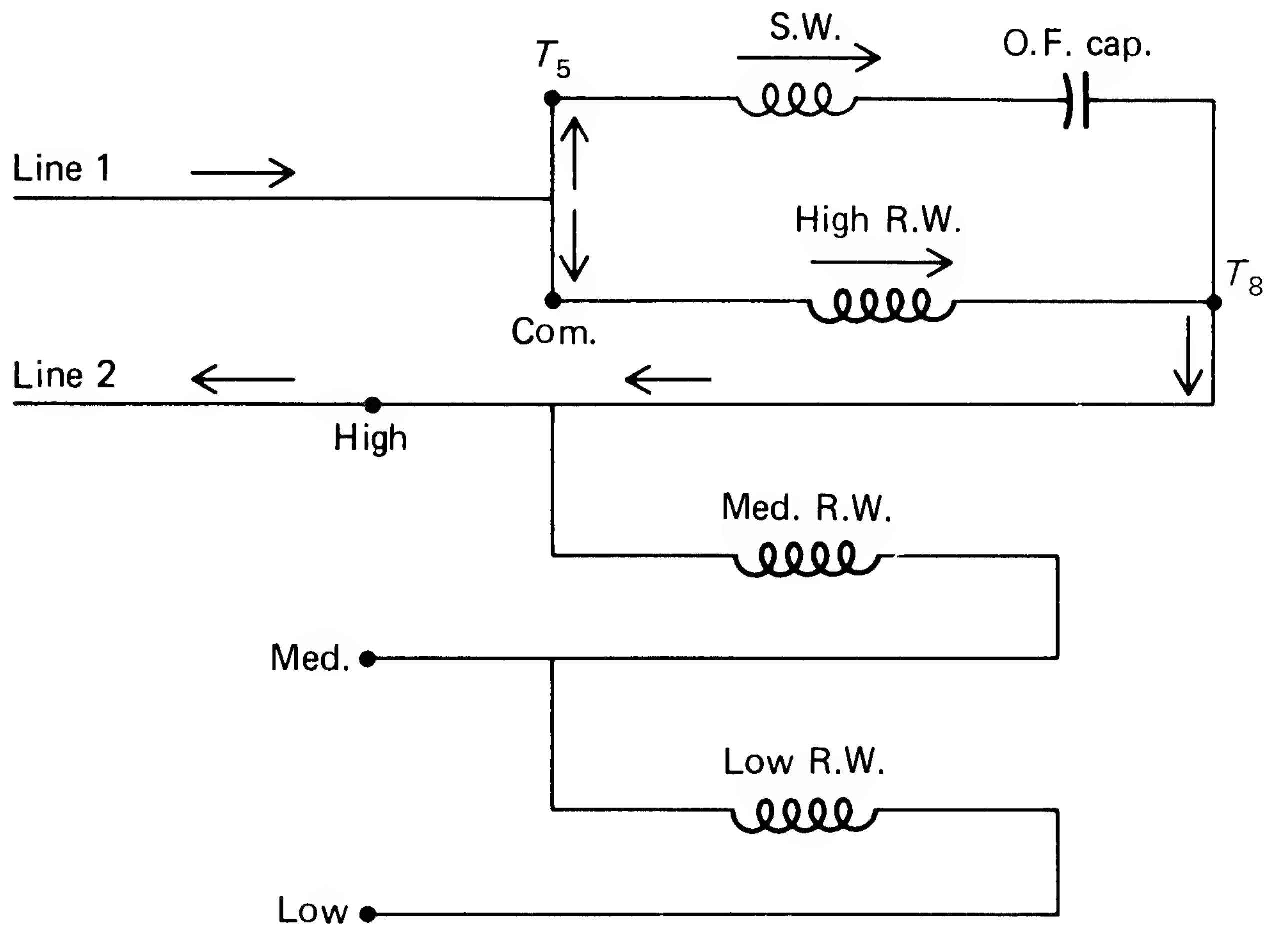


Fig. 1–178. Schematic of a three-speed permanent-split capacitor motor connected for high speed.

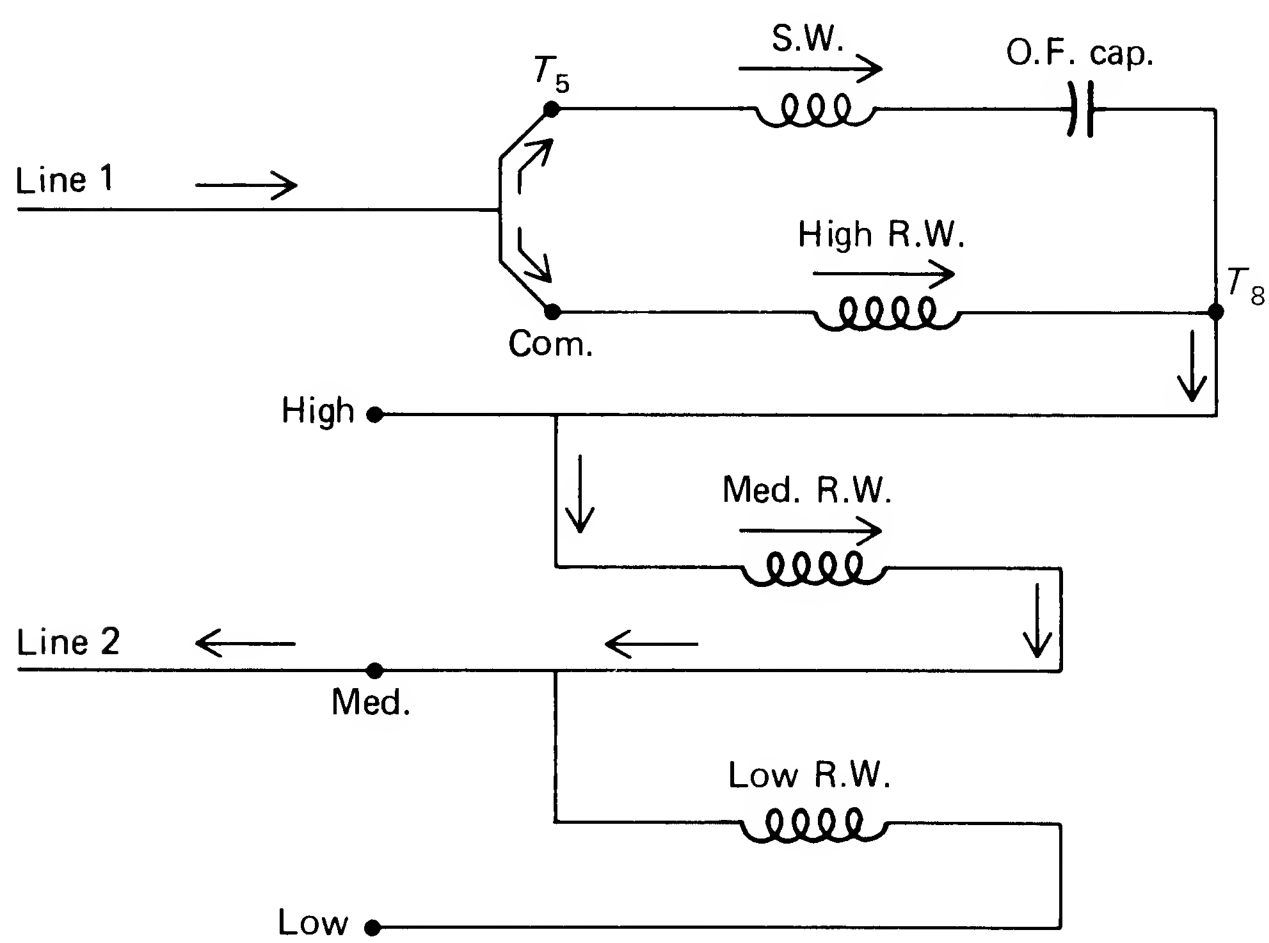


Fig. 1–179. Schematic of a three-speed permanent-split capacitor motor connected for medium speed.

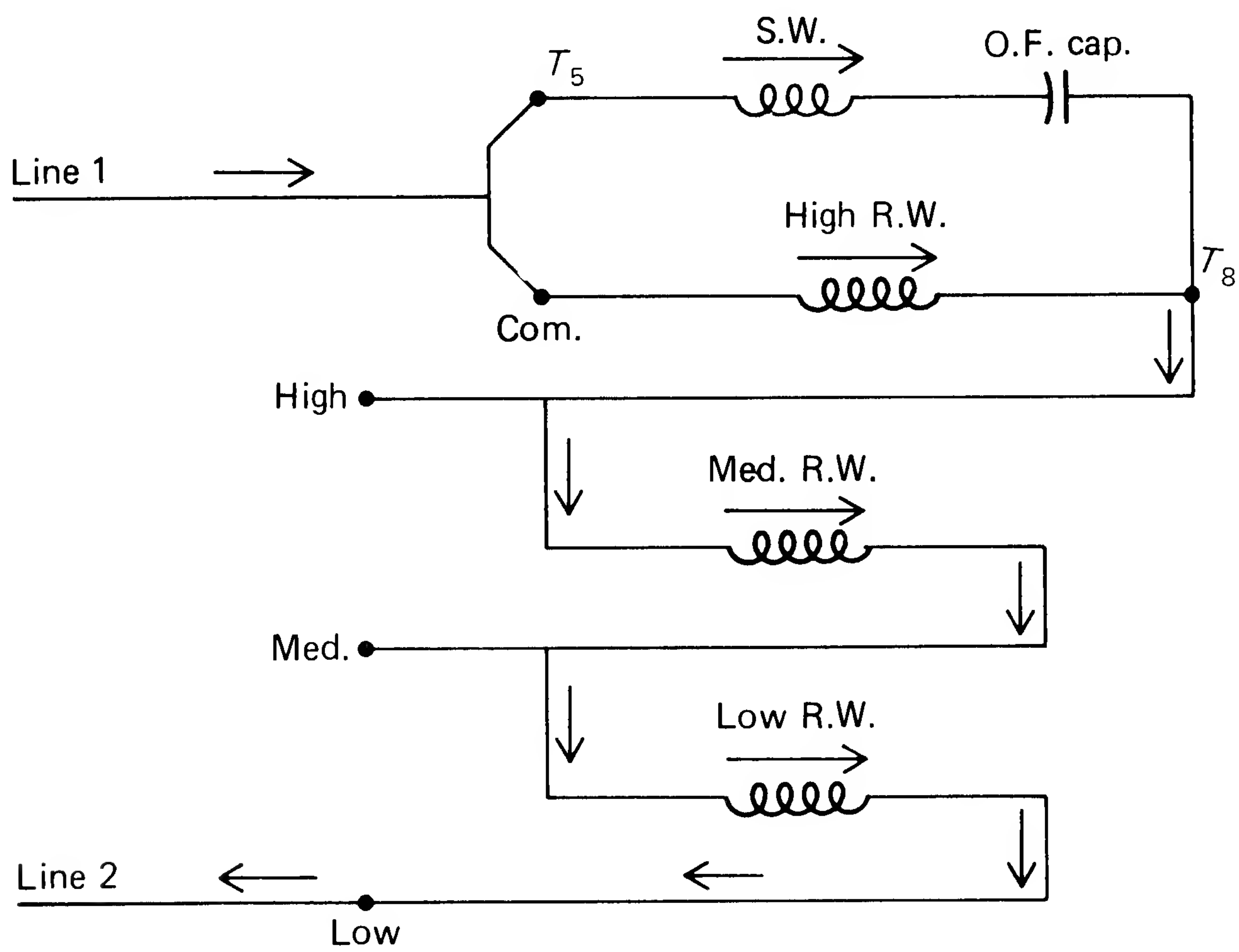
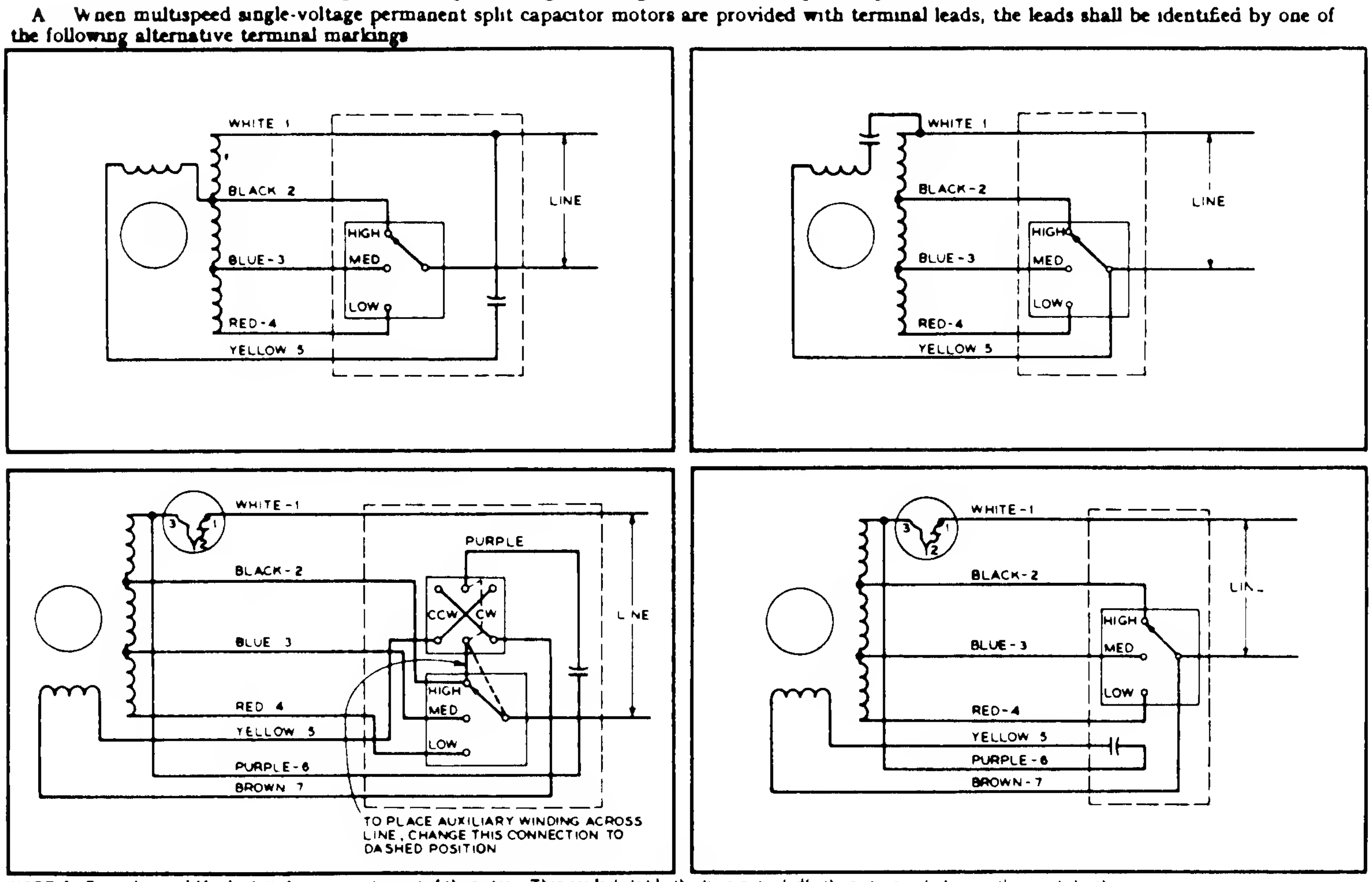


Fig. 1-180. Schematic of a three-speed permanent-split capacitor motor connected for low speed.

Terminal Markings—Multispeed Single-voltage Permanent-split Capacitor Motors

A When multispeed single-voltage permanent split capacitor motors are provided with terminal leads, the leads shall be identified by one of the following alternative terminal markings



NOTE I—Parts shown within the dotted area are not a part of the motor They are included in the diagram to clarify the motor terminal connections made by the user
NOTE II—For two speed motors omit terminal 4 (red) and the corresponding winding

FRACTIONAL-HORSEPOWER MOTORS FOR AIR CONDITIONING CONDENSERS AND EVAPORATOR FANS

Fig. 1-181. Terminal markings—multispeed single-voltage permanent-split capacitor motors.

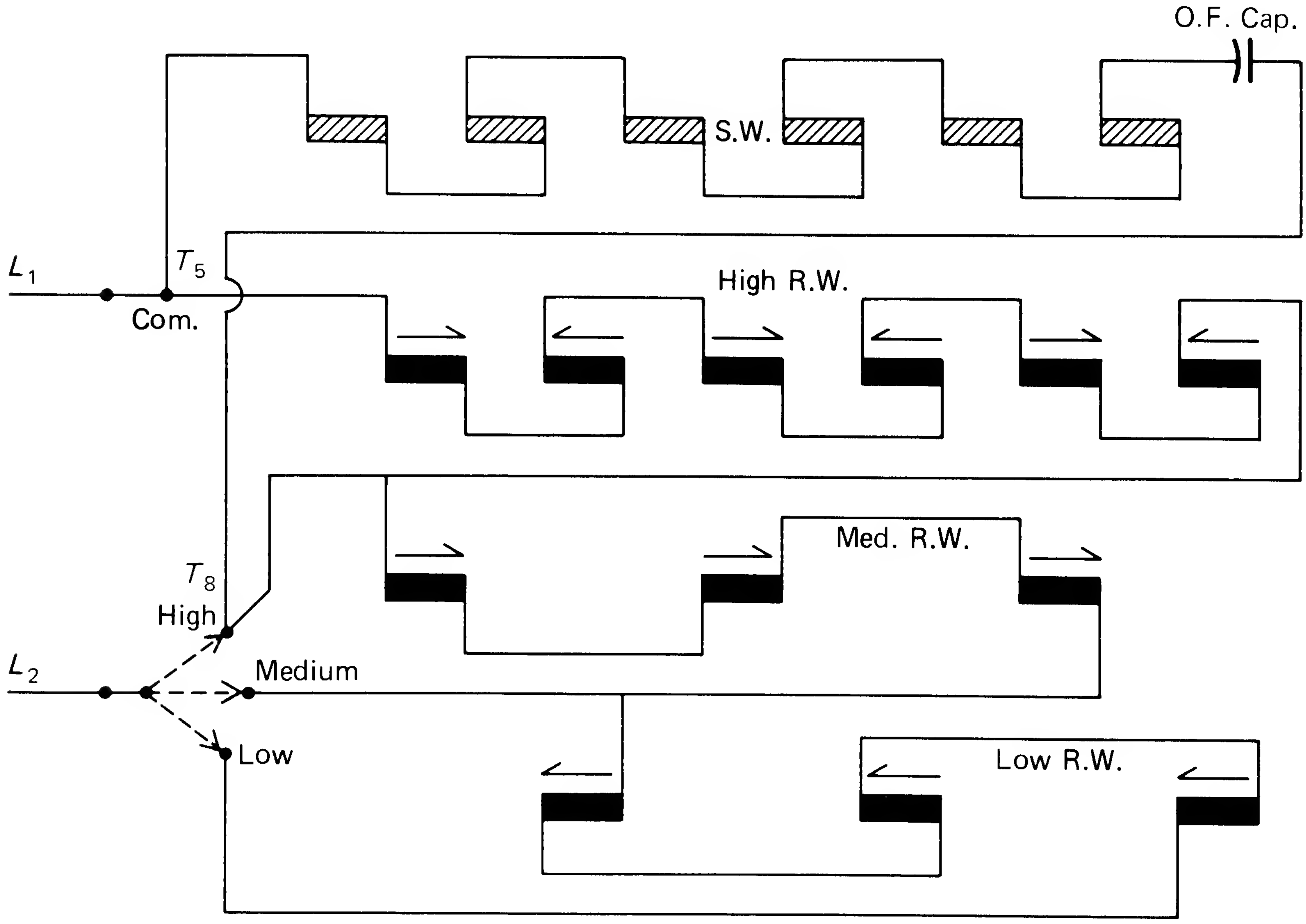


Fig. 1-182. Wiring diagram of a three-speed capacitor-run motor.

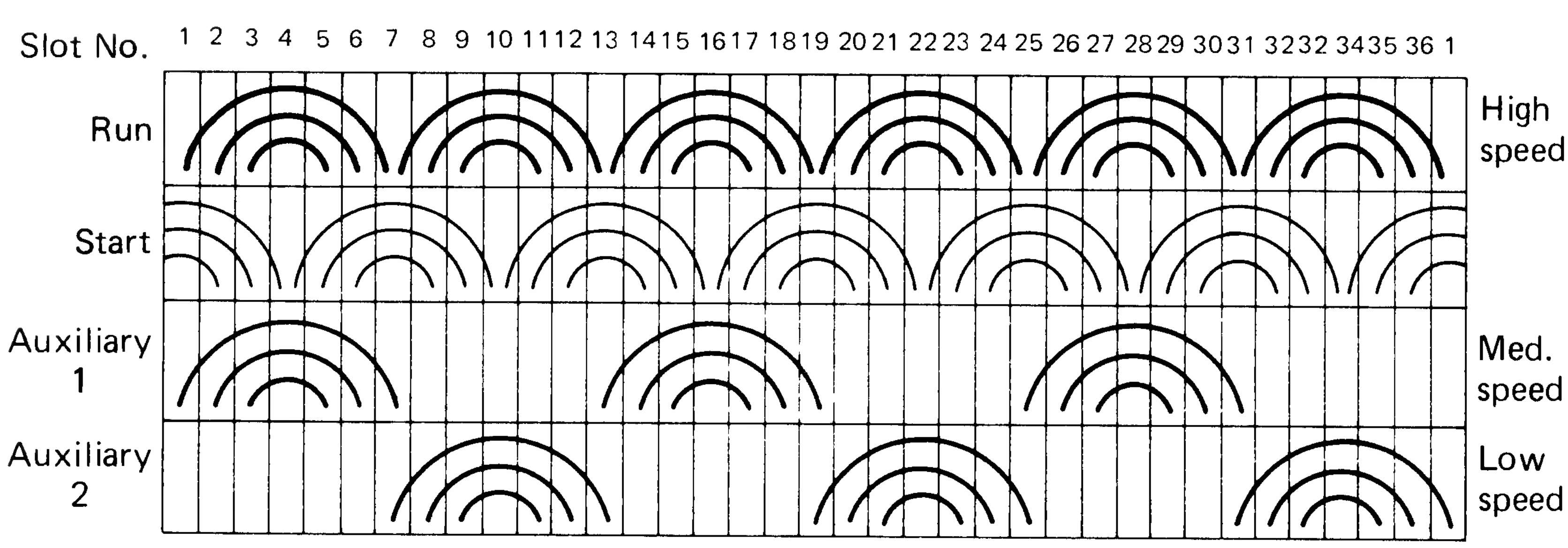


Fig. 1-183. A typical layout of a three-speed capacitor-run motor.

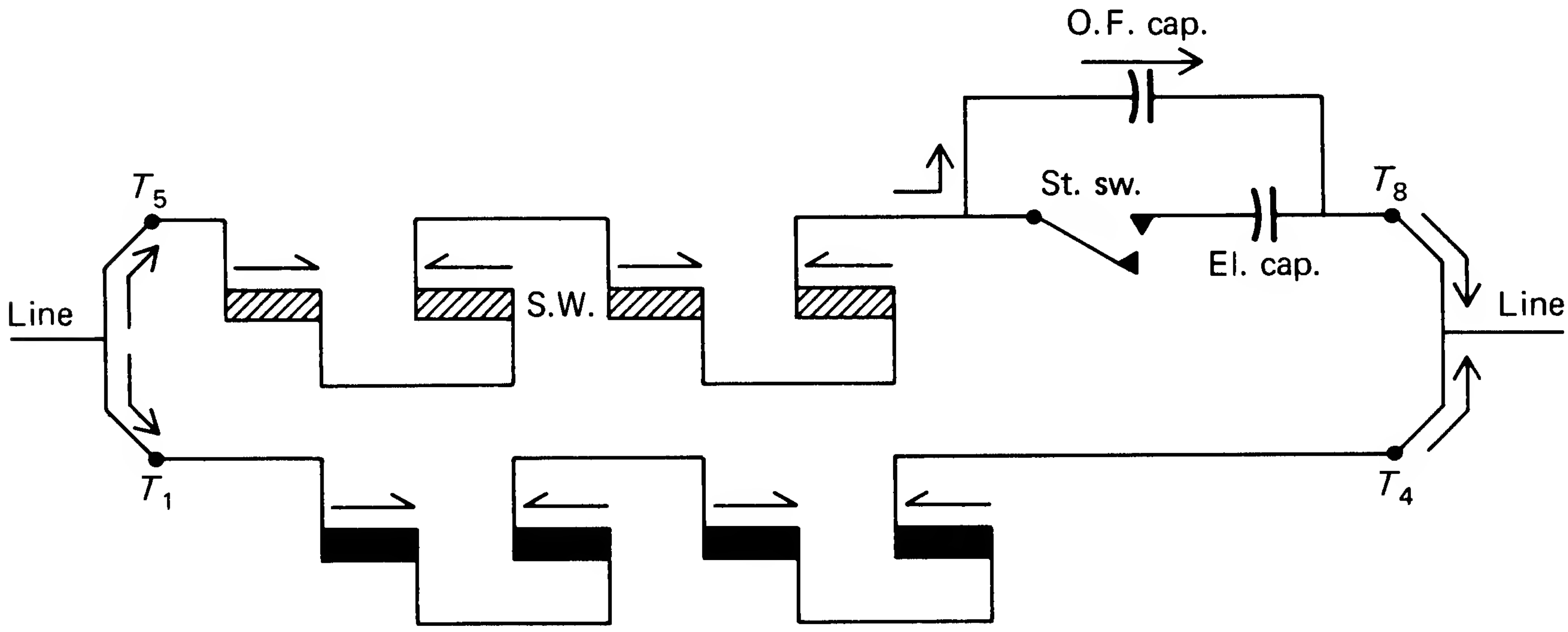


Fig. 1-184. Two-value capacitor motor showing the path of the current when the motor is running.

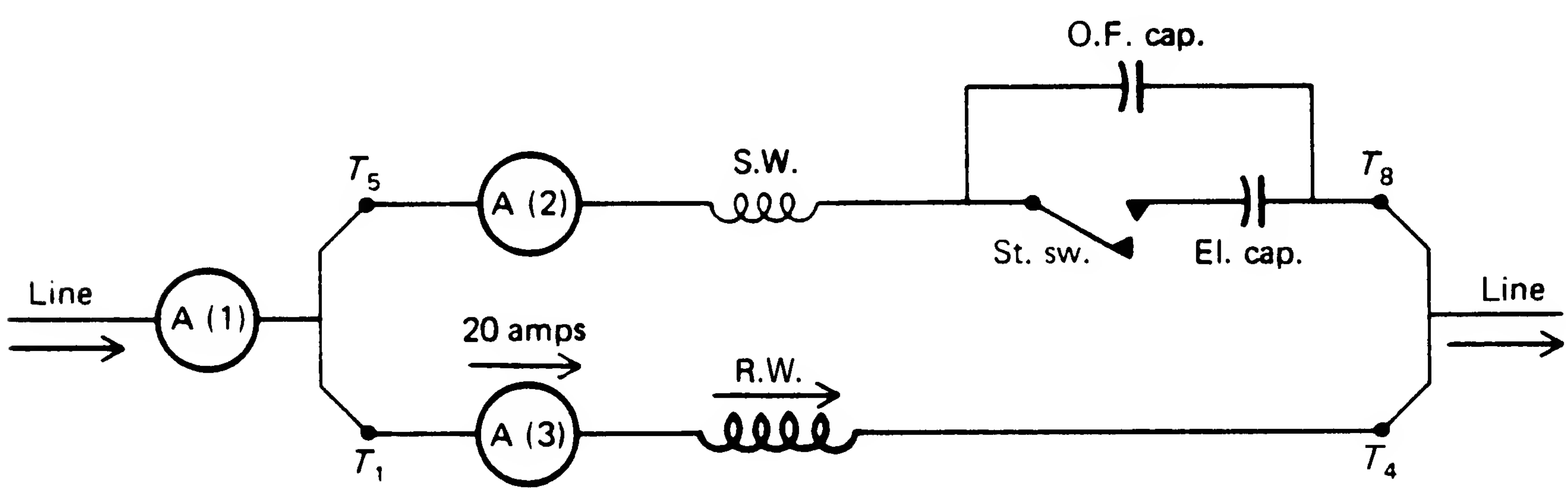


Fig. 1-185. Schematic of a two-value capacitor motor using two capacitors.

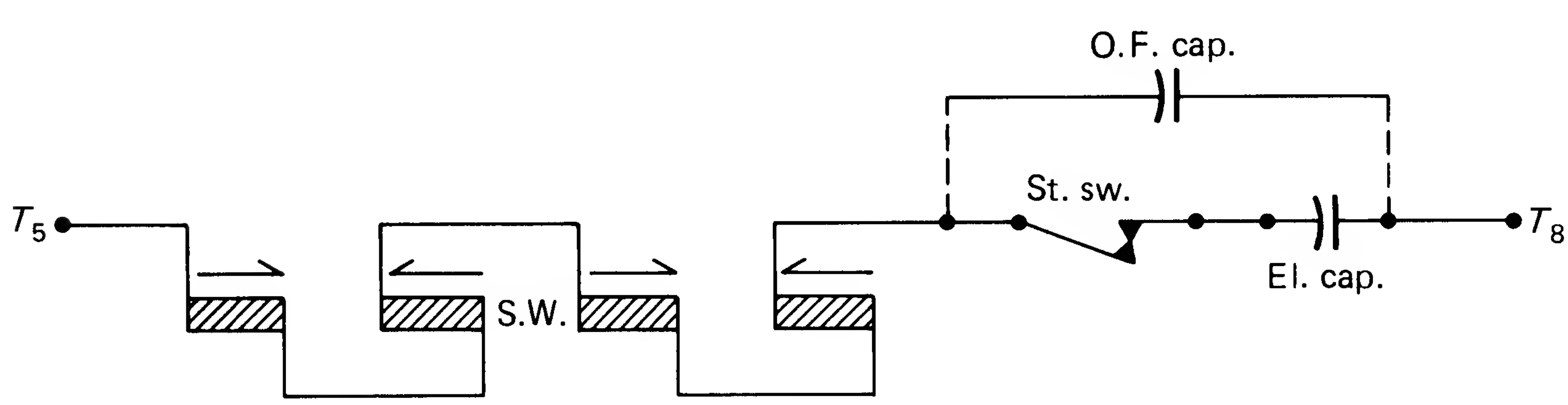


Fig. 1-186. Single-voltage start-winding connection. The voltage rating can be high or low.

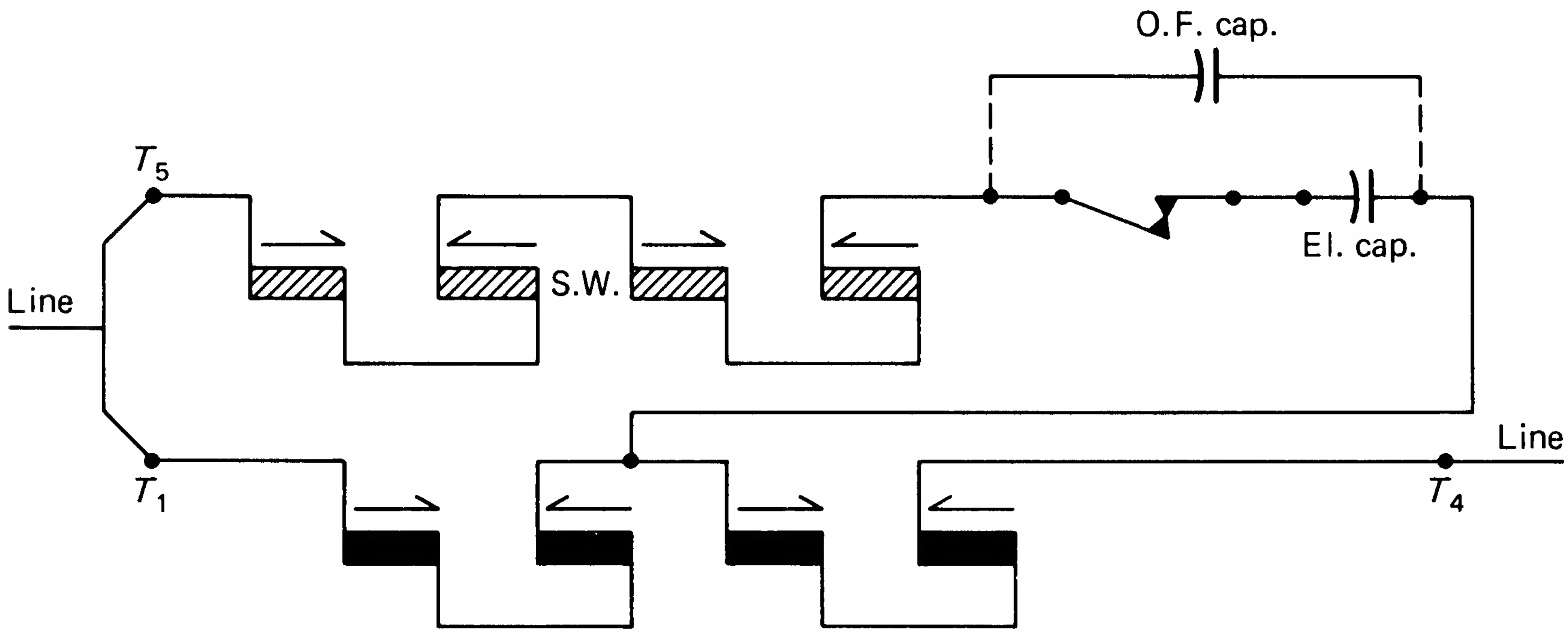


Fig. 1–187. Low voltage start-winding connected to the center of the run winding. This is a high-voltage motor. The electrolytic capacitor is rated for low voltage.

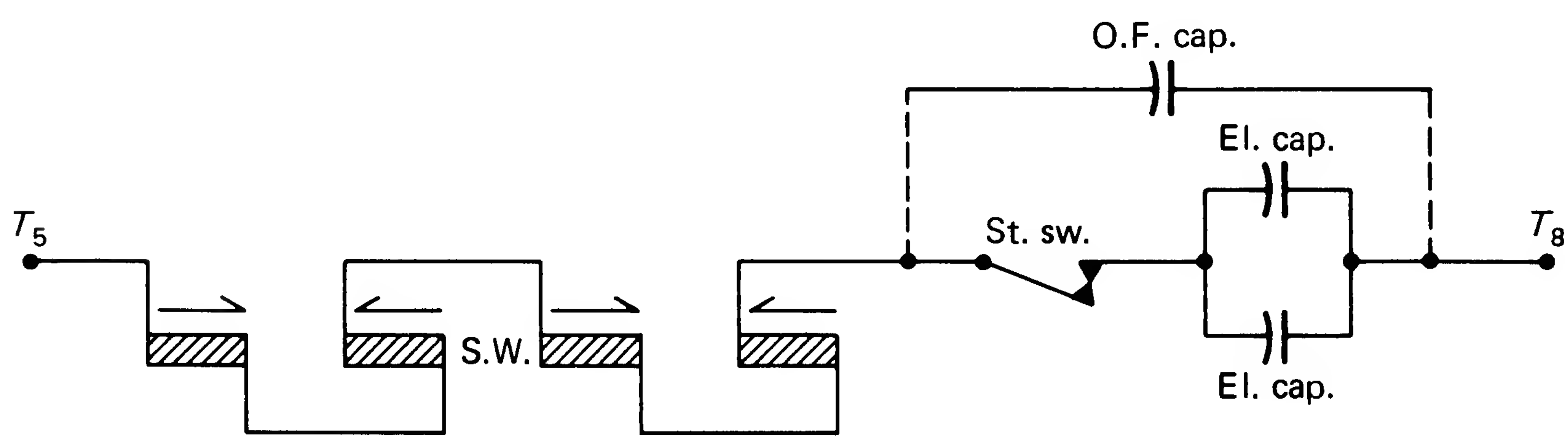


Fig. 1–188. Single-voltage start winding with two electrolytic capacitors in parallel.

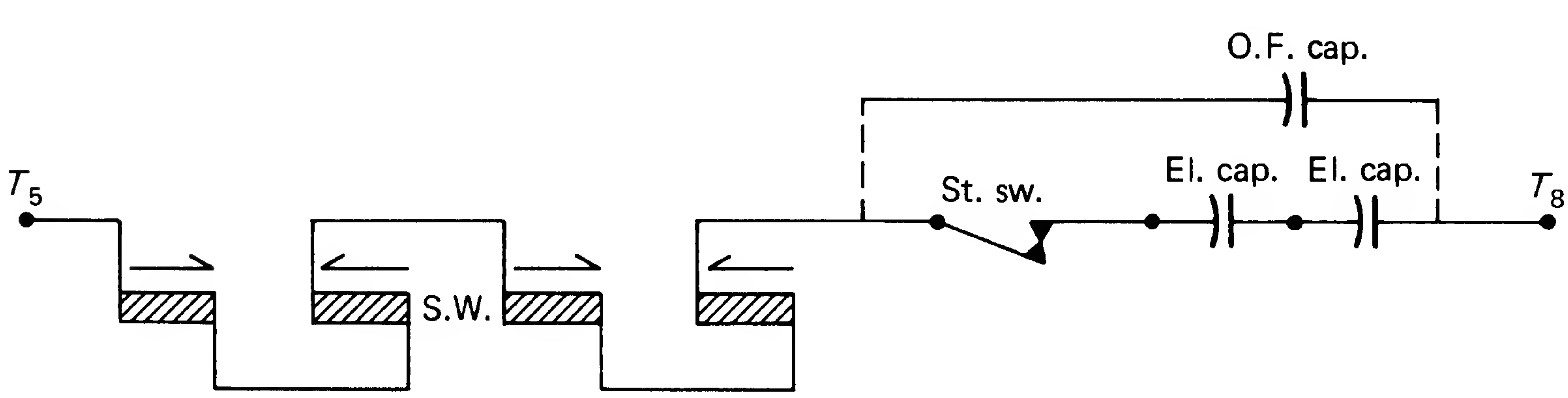


Fig. 1–189. High-voltage start winding using two low-voltage capacitors in series.

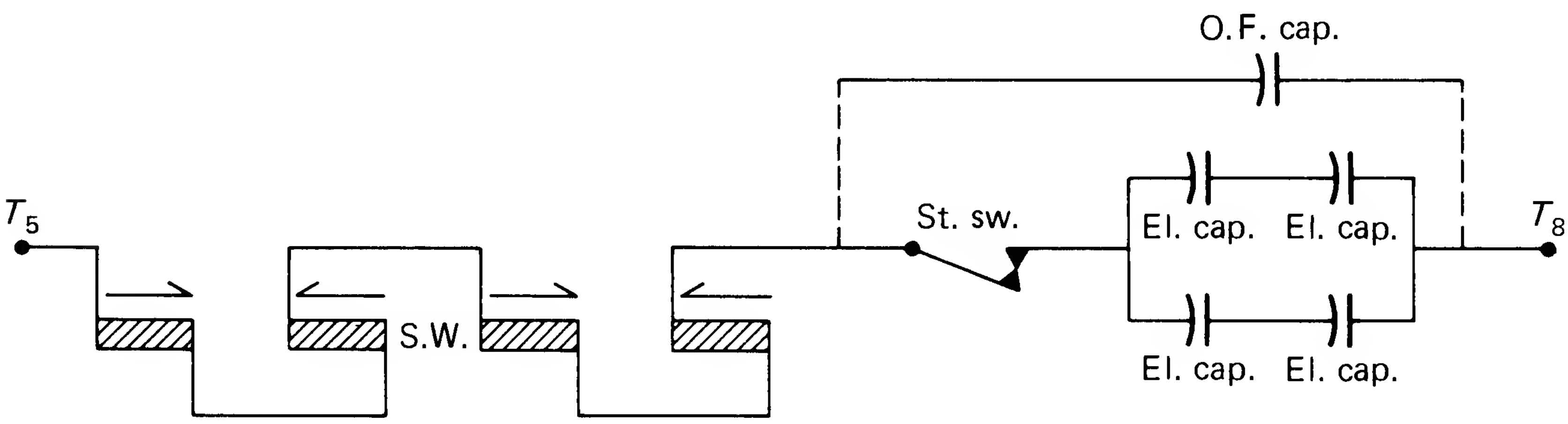


Fig. 1-190. High-voltage start winding using two low-voltage capacitors in series, in parallel with two low-voltage capacitors in series.

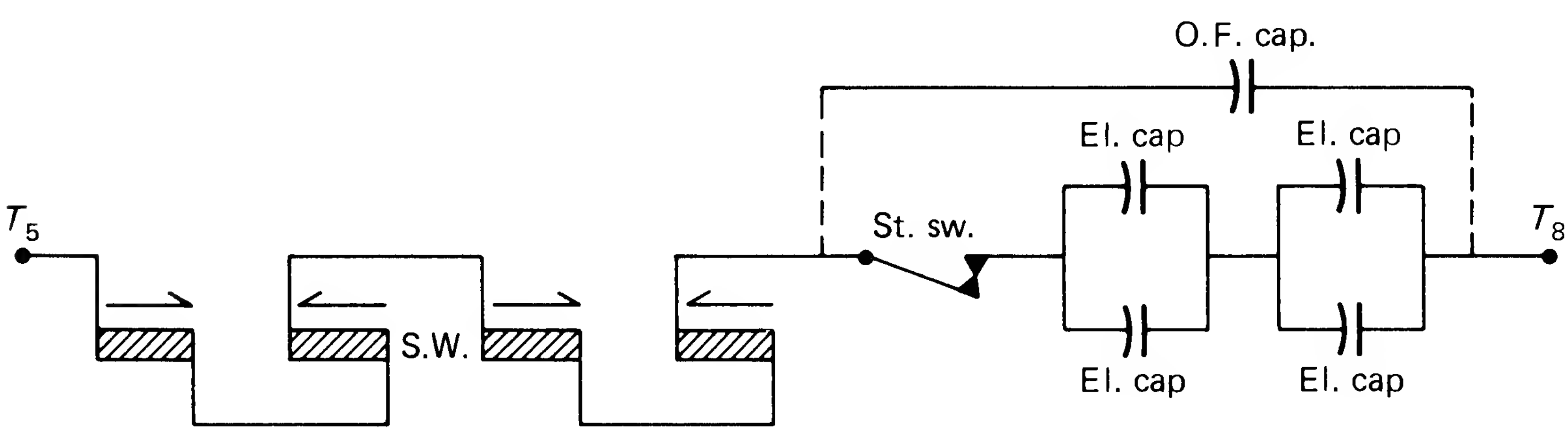


Fig. 1-191. High-voltage winding with two capacitors connected in parallel, in series with two capacitors connected in parallel. The electrolytic capacitors all are low voltage.

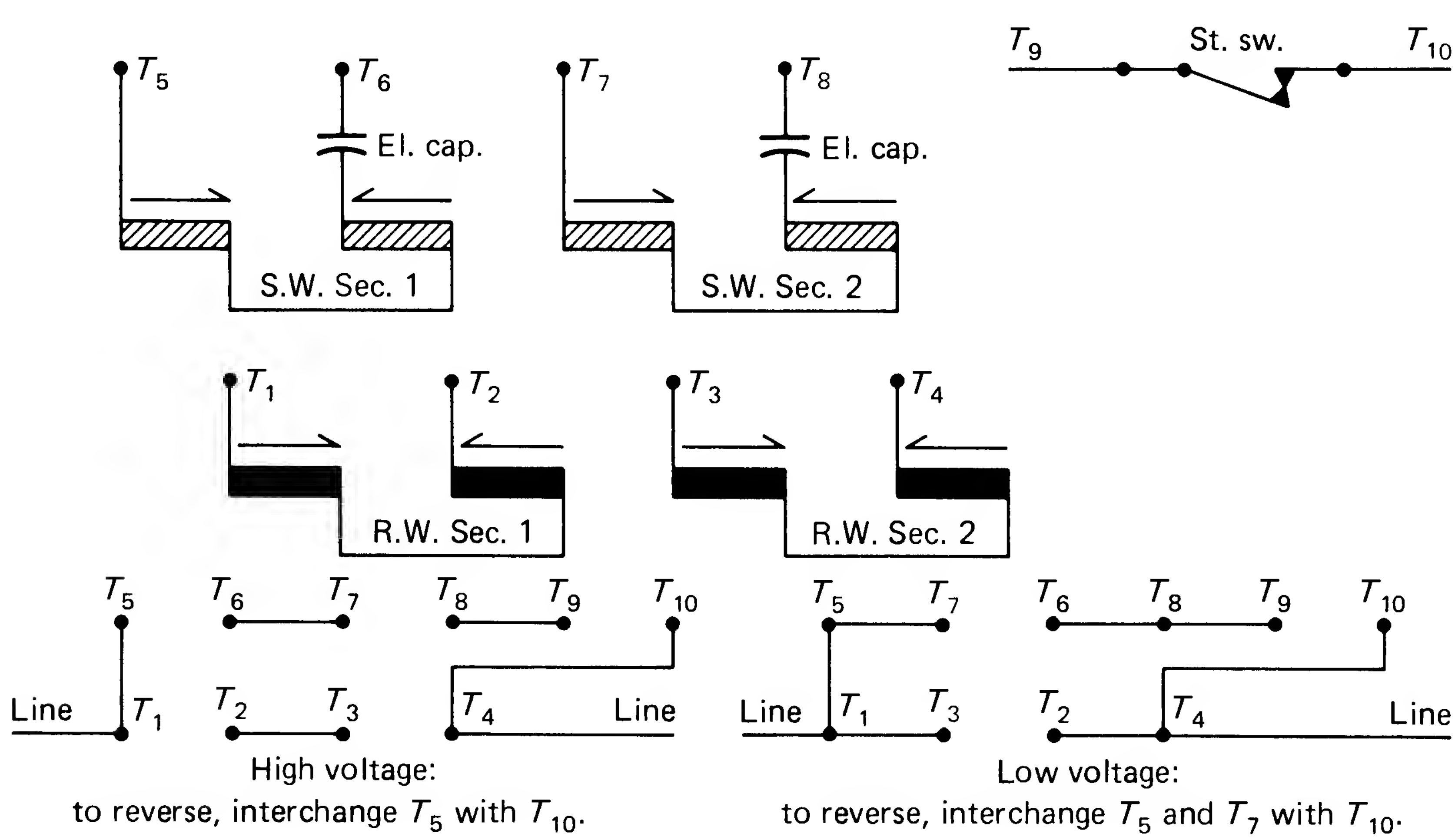


Fig. 1-192. Dual-voltage motor with a dual-voltage start winding controlled by a stationary switch with one set of contacts.

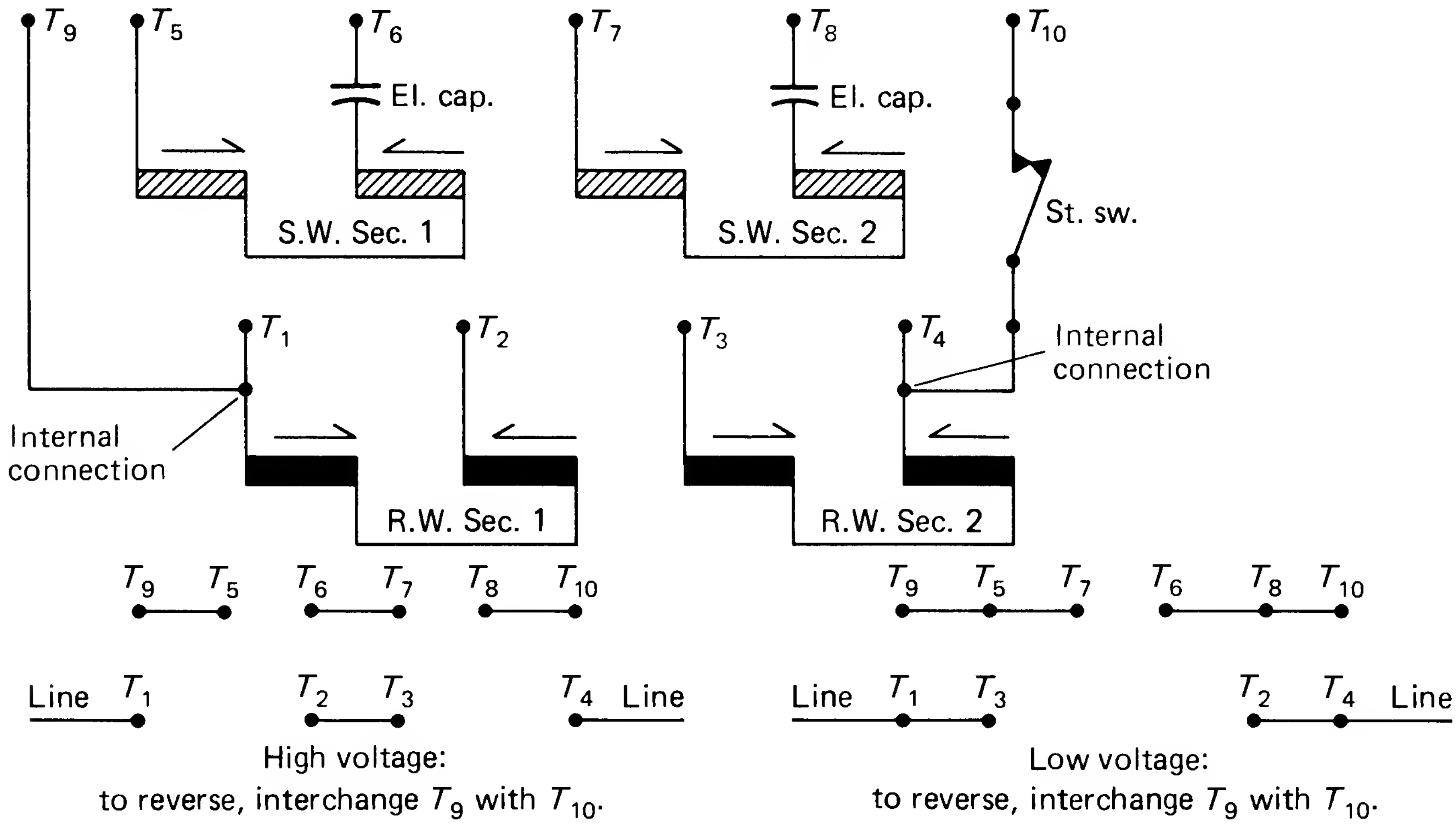


Fig. 1-193. Dual-voltage capacitor-start motor with a dual-voltage start winding controlled by a stationary switch connected internally to T_4. T_9 is connected internally to T_1.

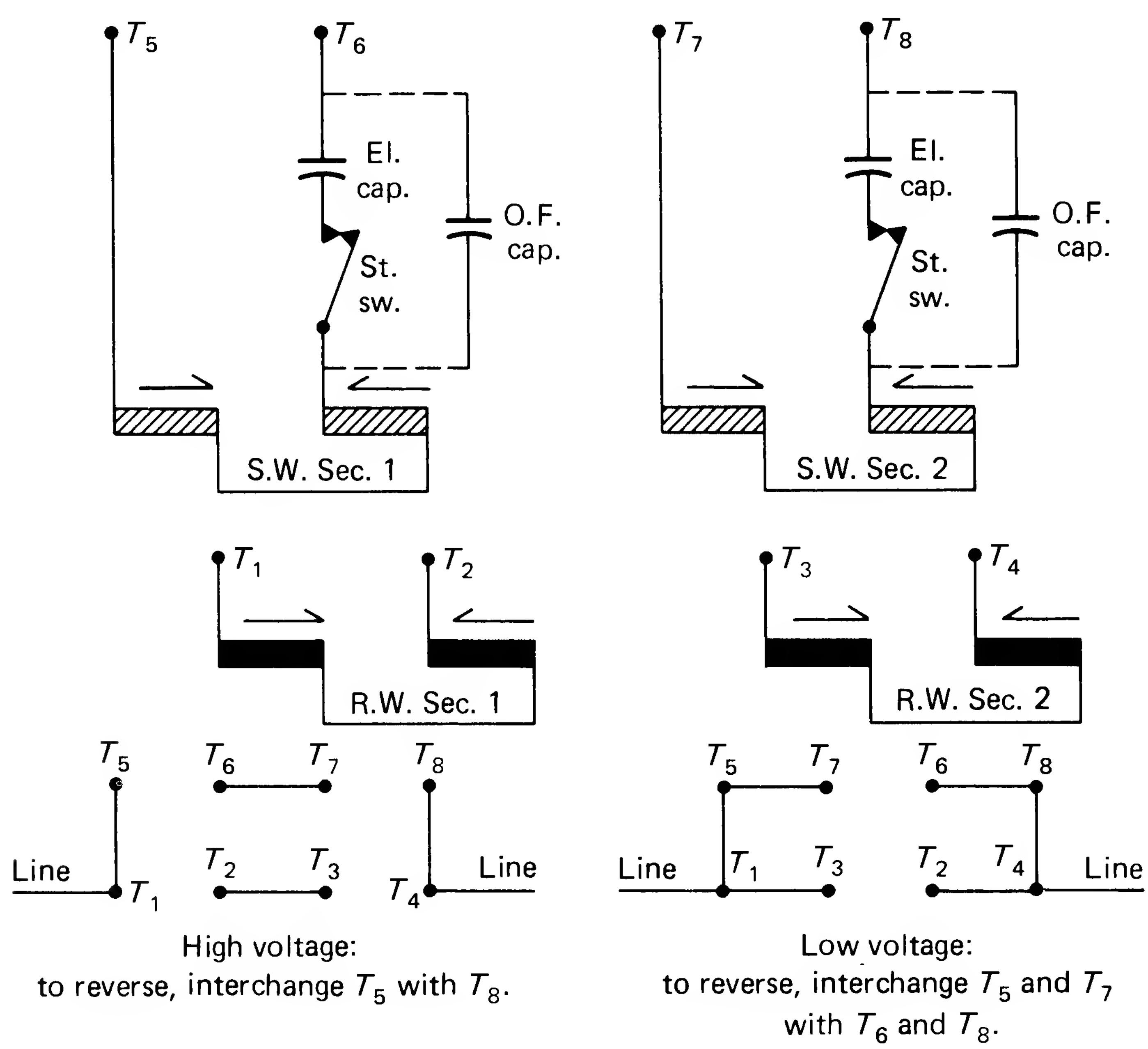


Fig. 1-194. Dual-voltage, capacitor-start motor with two sets of stationary switch contacts controlling the start winding.

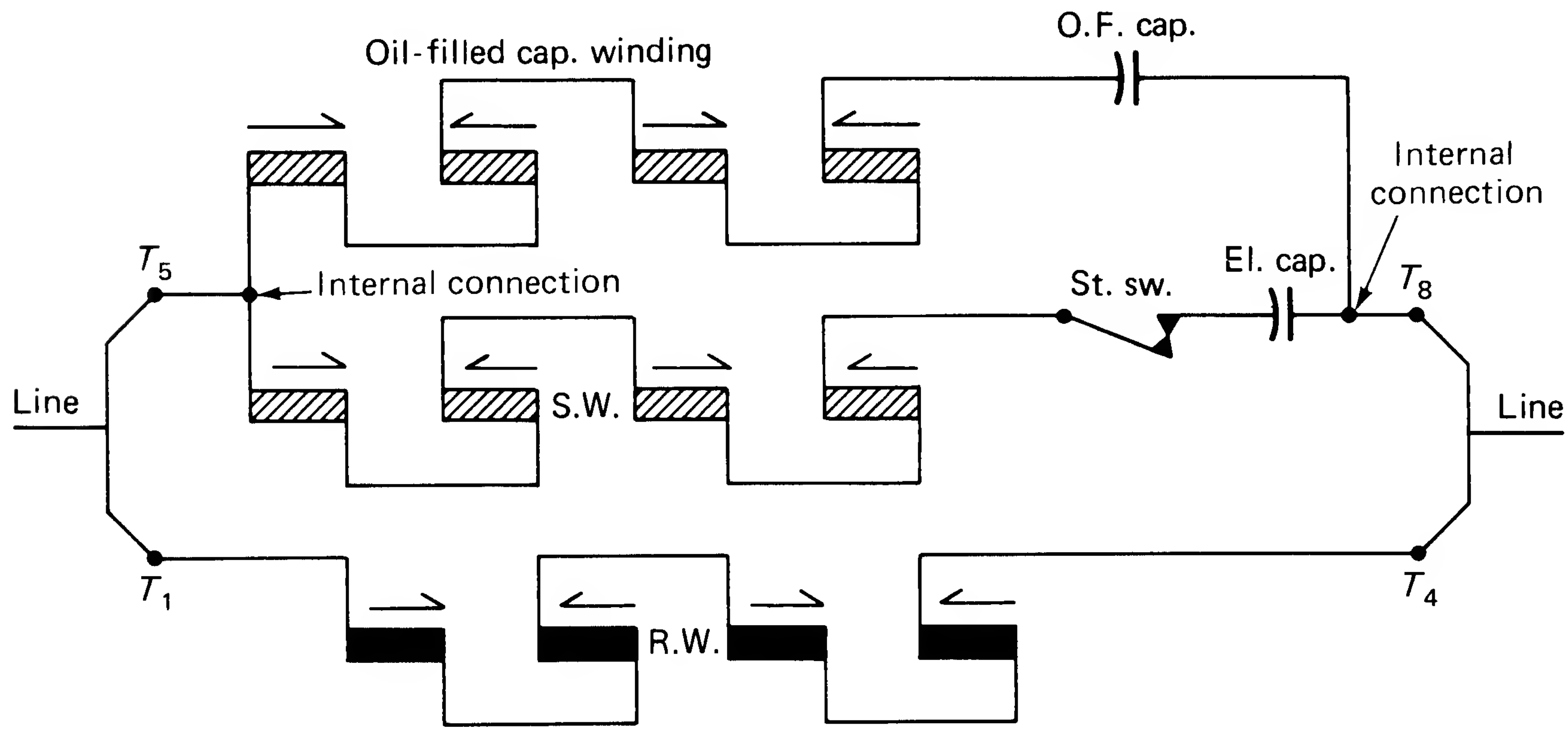


Fig. 1-195. Two-value capacitor-start motor with a separate winding for the oil-filled capacitor.

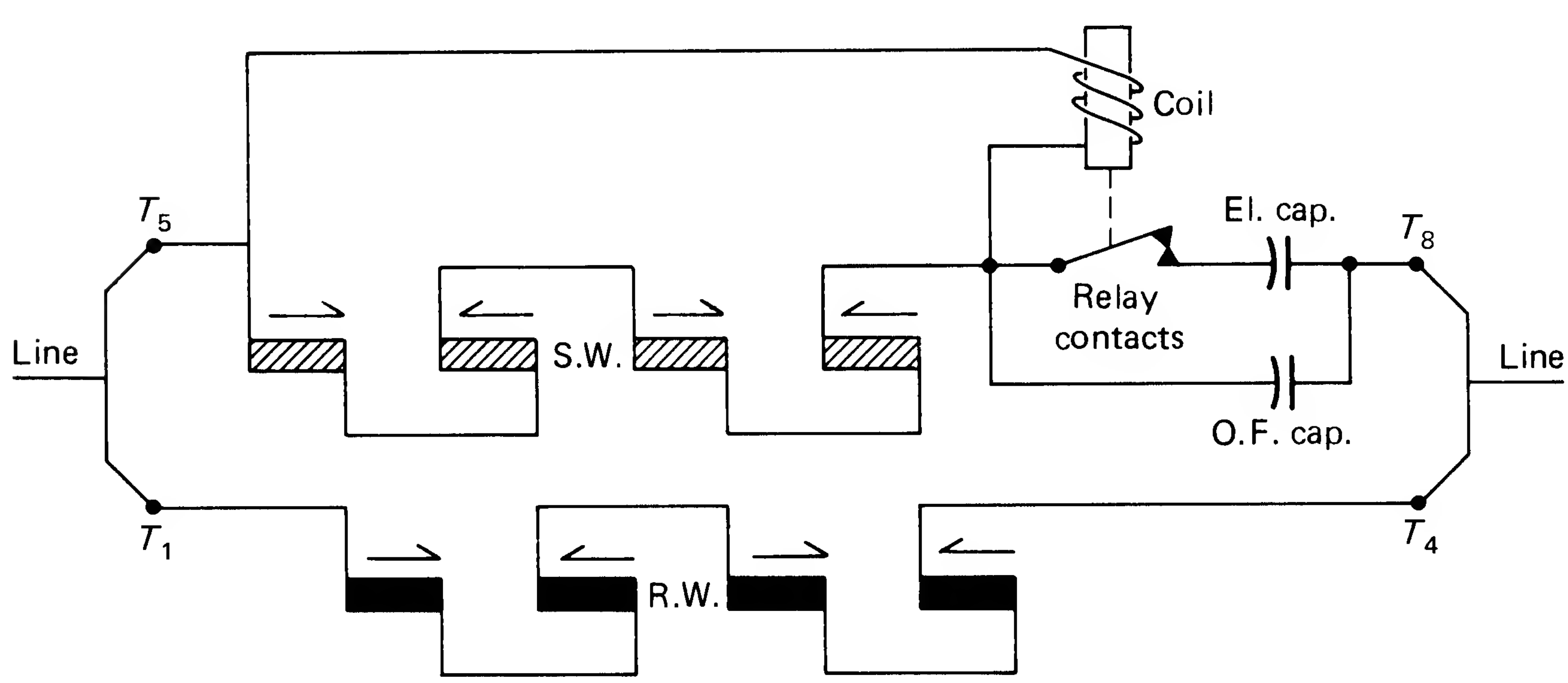


Fig. 1-196. Two-value capacitor-start motor with a potential relay controlling the start winding.

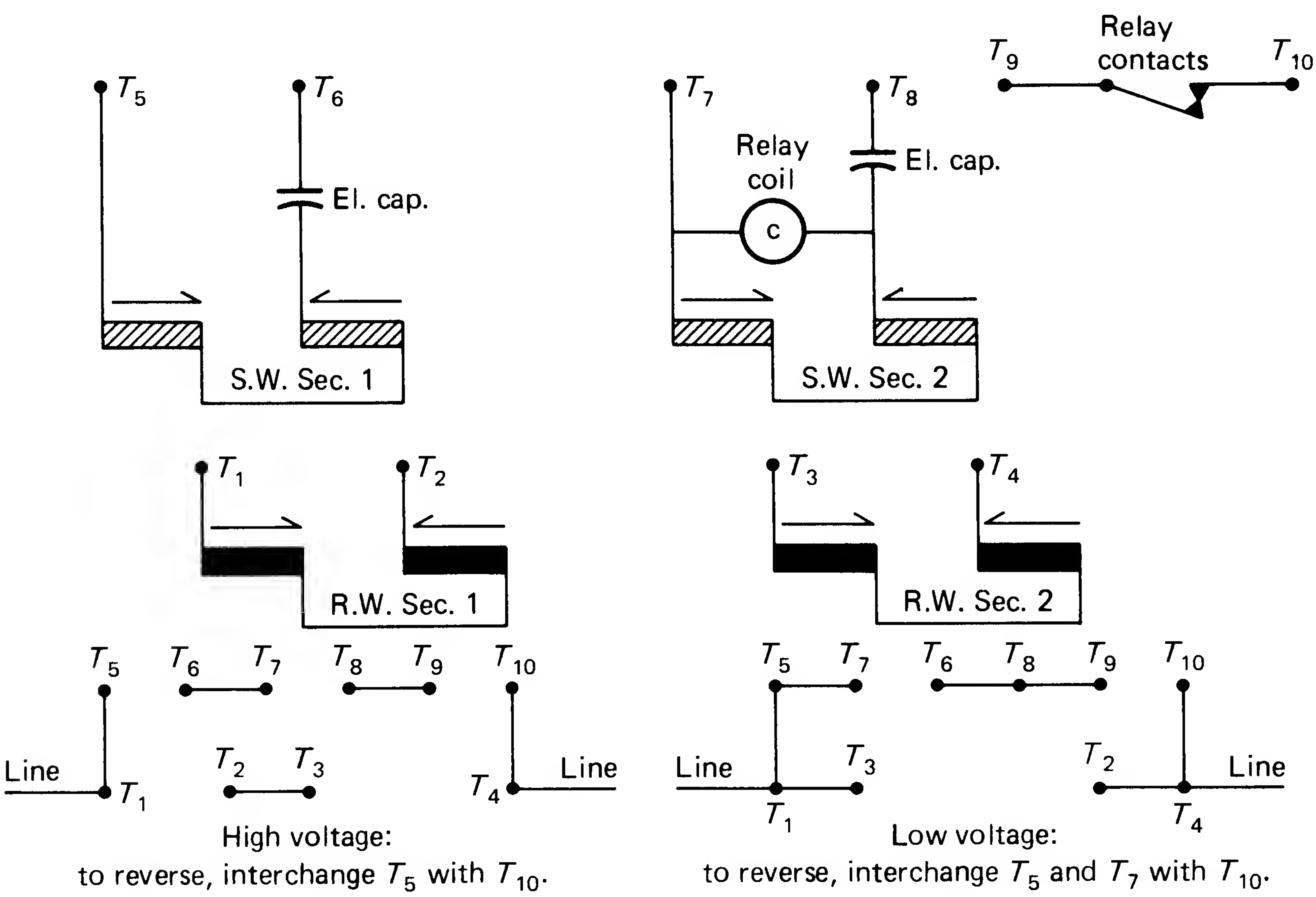


Fig. 1-197. Dual-voltage capacitor-start motor with a dual-voltage start winding controlled by a potential relay with one set of contacts. The potential relay is rated for low voltage.

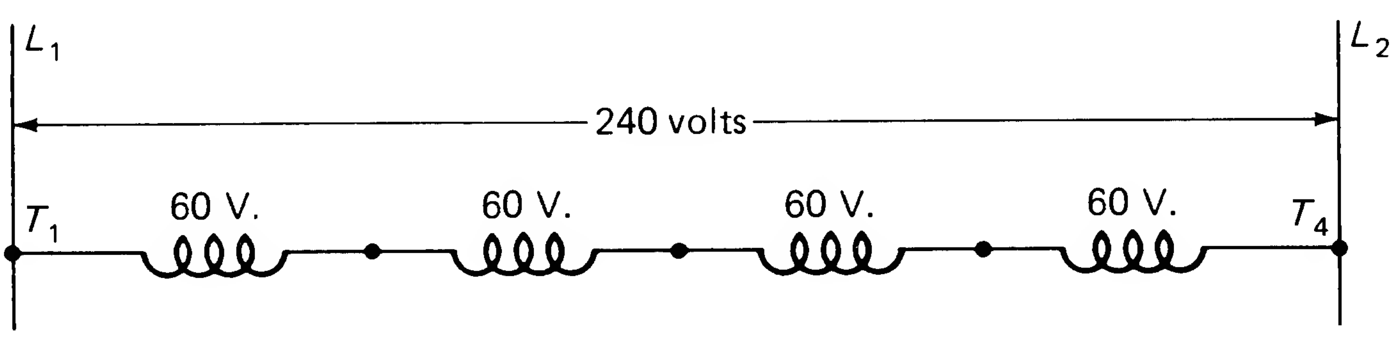


Fig. 1-198. Series connection of coils for 240-volt operation.

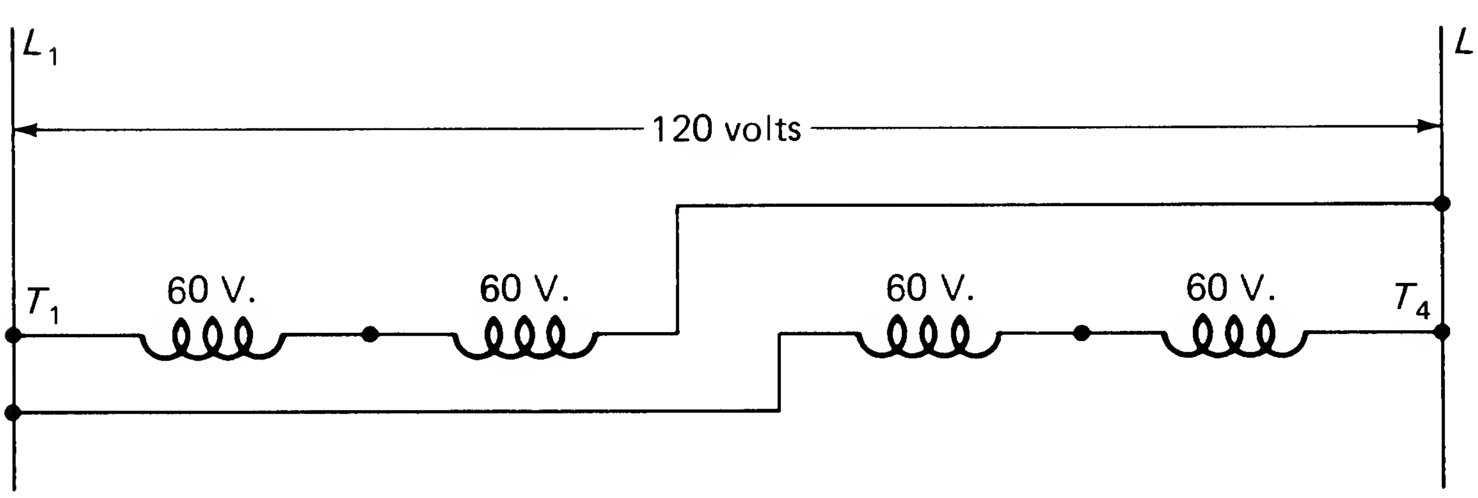


Fig. 1-199. Parallel connection of coils for 120-volt operation. Voltage remains the same across each coil.

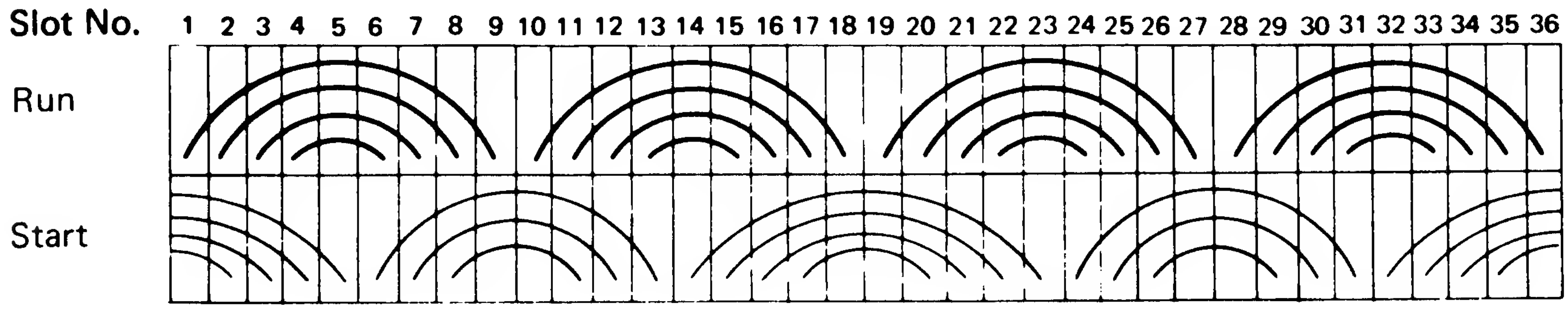


Fig. 1–200. Pitch data of a 36-slot, four-pole motor. The poles of the starting winding are not the same; one pole has four coils, and the next has three.

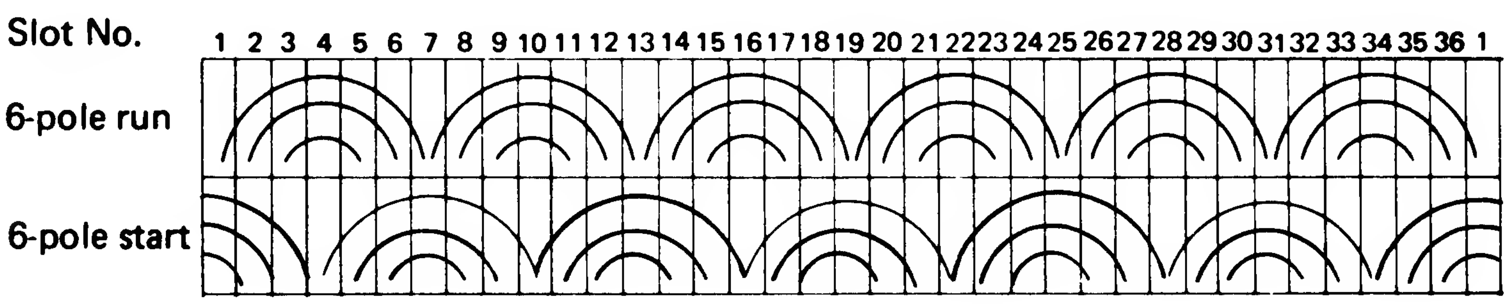


Fig. 1–201. Pitch data of a 36-slot, six-pole motor. The outer coils of each pole group lap one another and share the same slot.

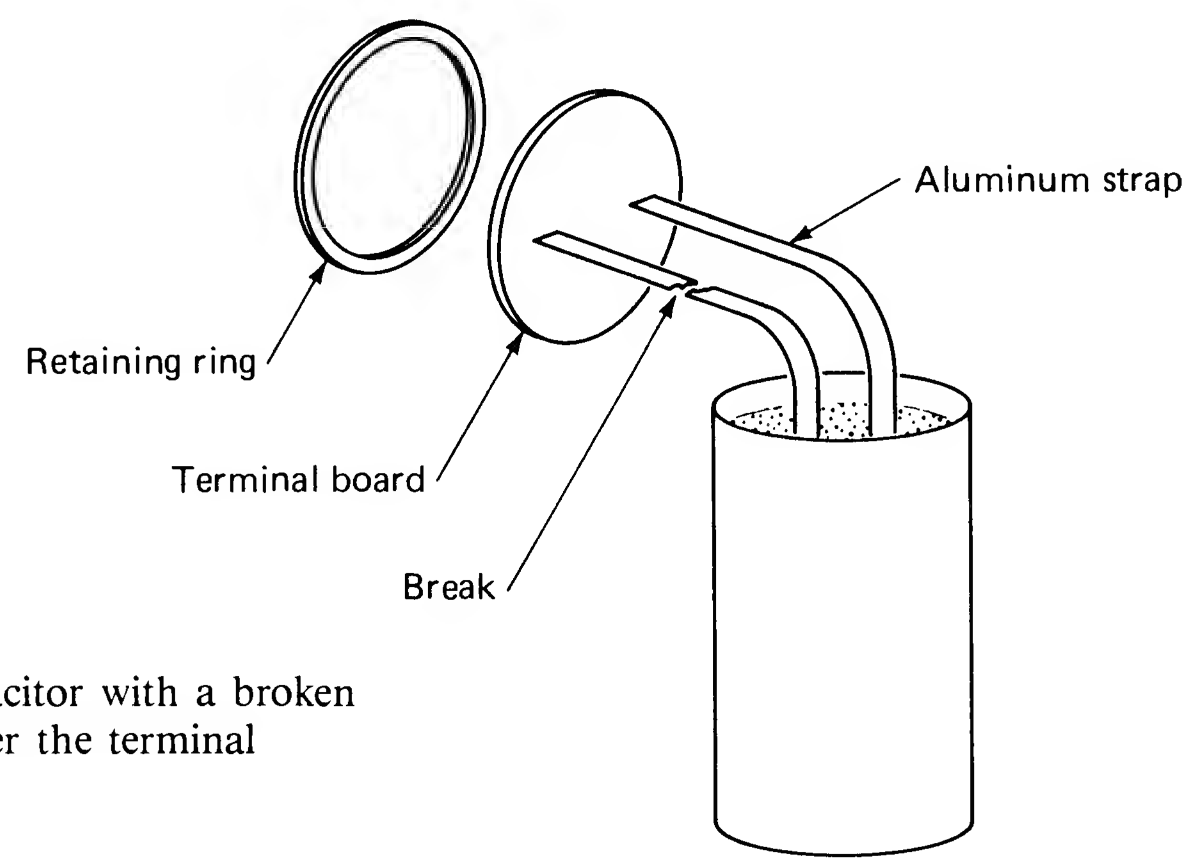


Fig. 1–202. Capacitor with a broken connecting strap under the terminal board.

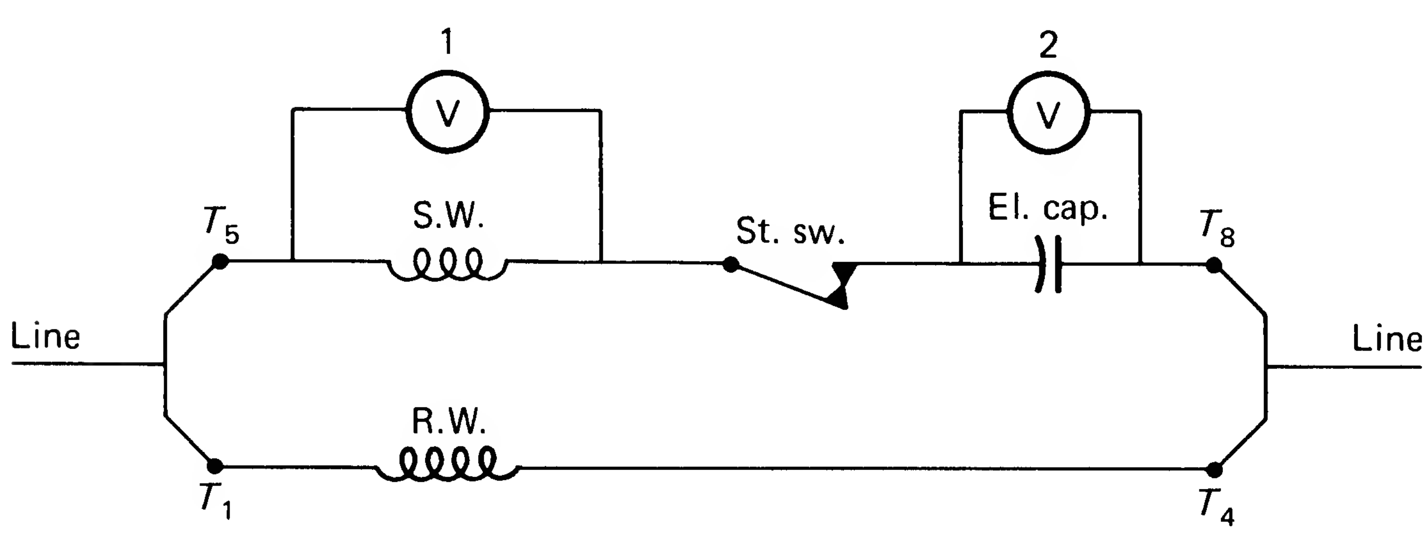


Fig. 1–203. Locked rotor method for finding the right-sized capacitor for a motor. Voltmeter 2 should read 5 to 10 percent higher than voltmeter 1.

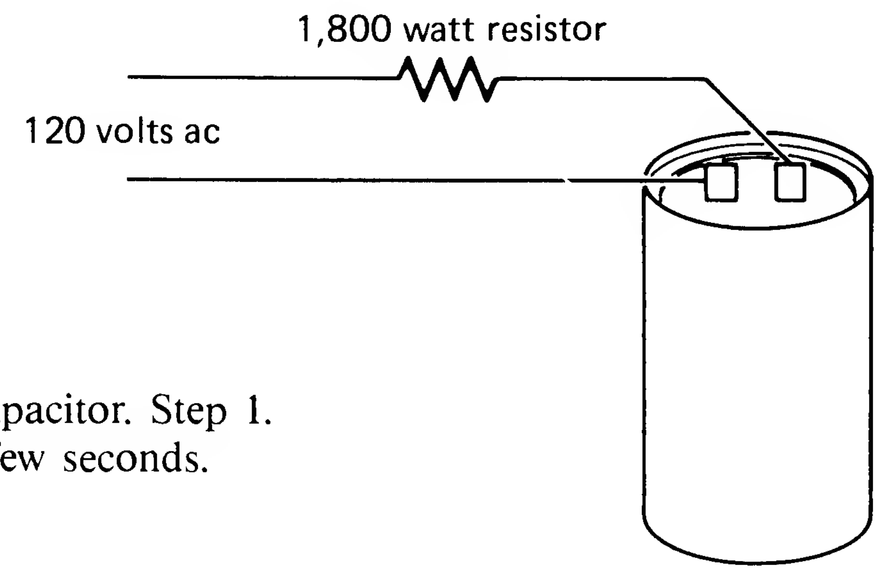


Fig. 1-204. Steps in testing a capacitor. Step 1. Connect capacitor, as shown, for a few seconds.

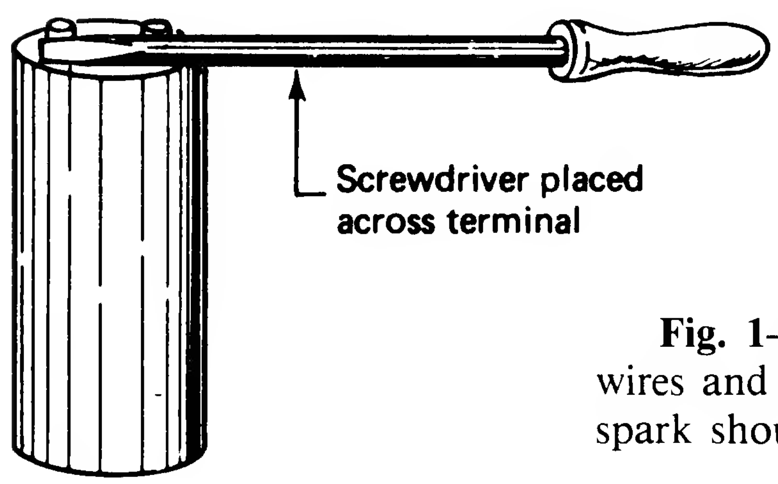
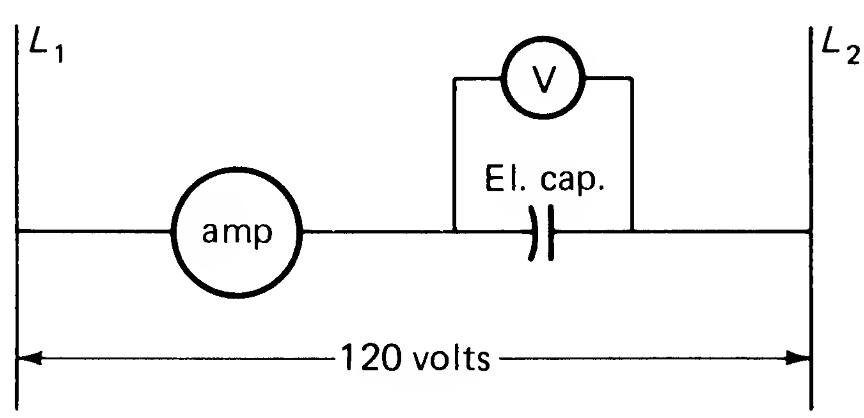


Fig. 1-205. Step 2. Remove line wires and short-circuit the terminals. A spark should be visible.

Fig. 1-206. Test used to determine a capacitor's value.



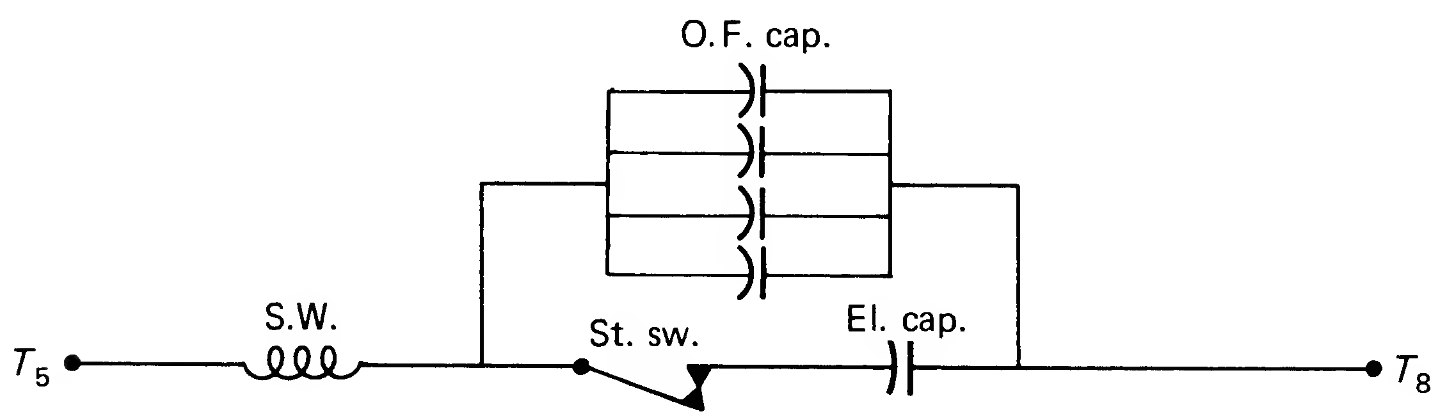


Fig. 1-207. Start-winding schematic of a two-value capacitor-start motor with four oil-filled capacitors and one electrolytic capacitor. Oil-filled capacitors are always connected in parallel to each other.

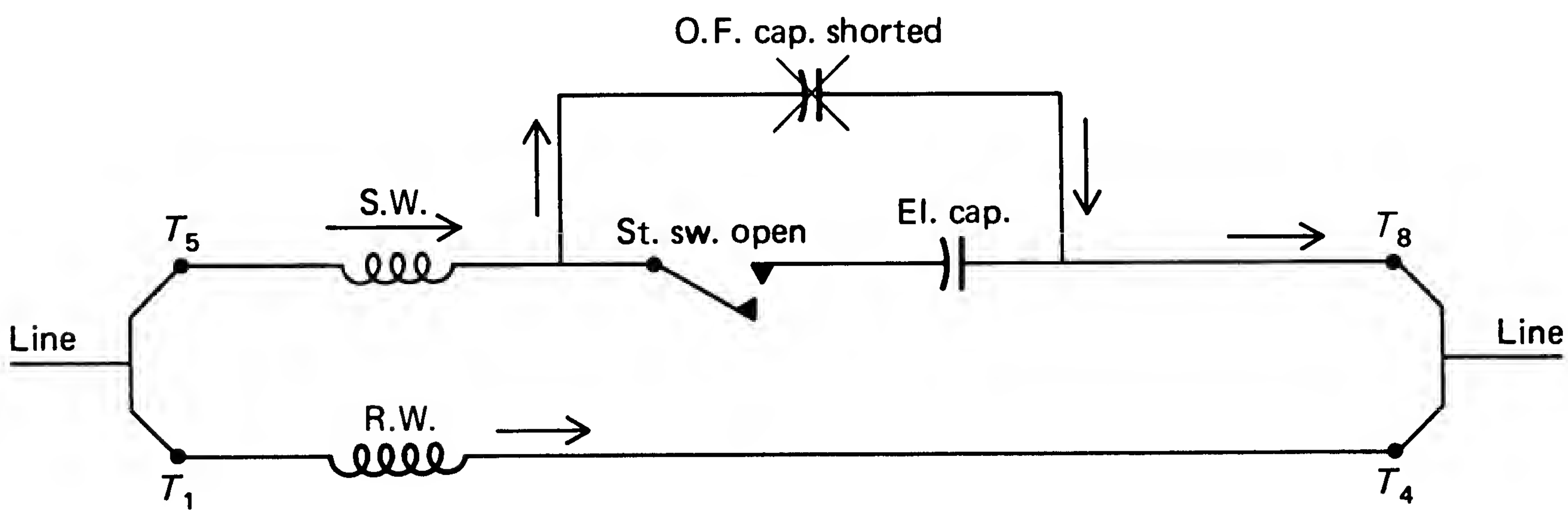


Fig. 1-208. If an oil-filled capacitor becomes shorted, a high current will flow in the start winding. If the circuit protection does not function, the winding will burn.

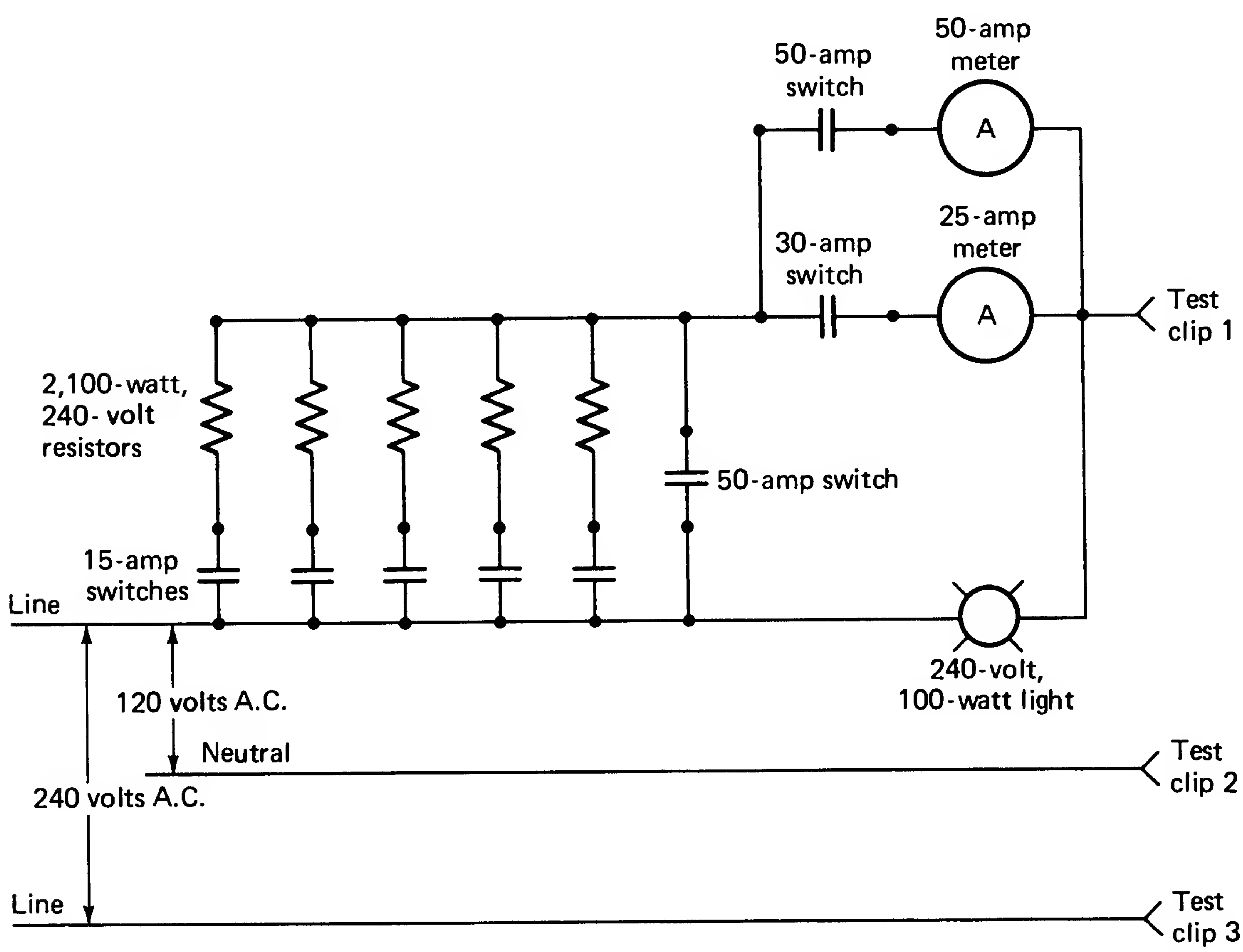


Fig. 1-209. Test panel. Test clips 1 and 2 are used for 120-volt testing, and test clips 1 and 3 are used for 240-volt testing.

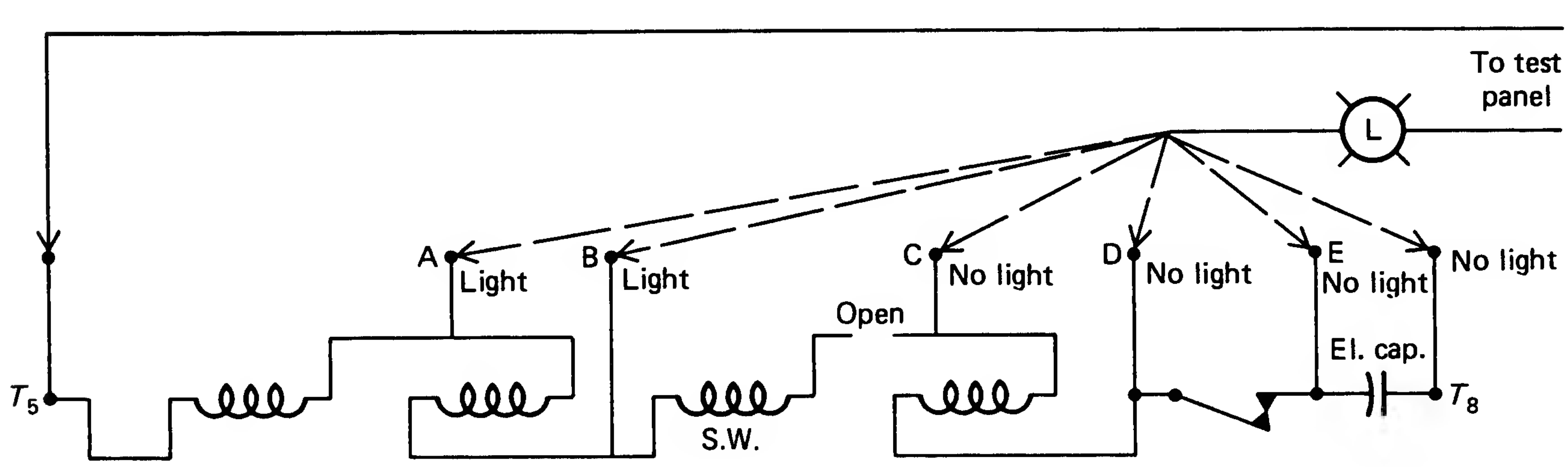


Fig. 1-210. Places to test for opens in a start winding.

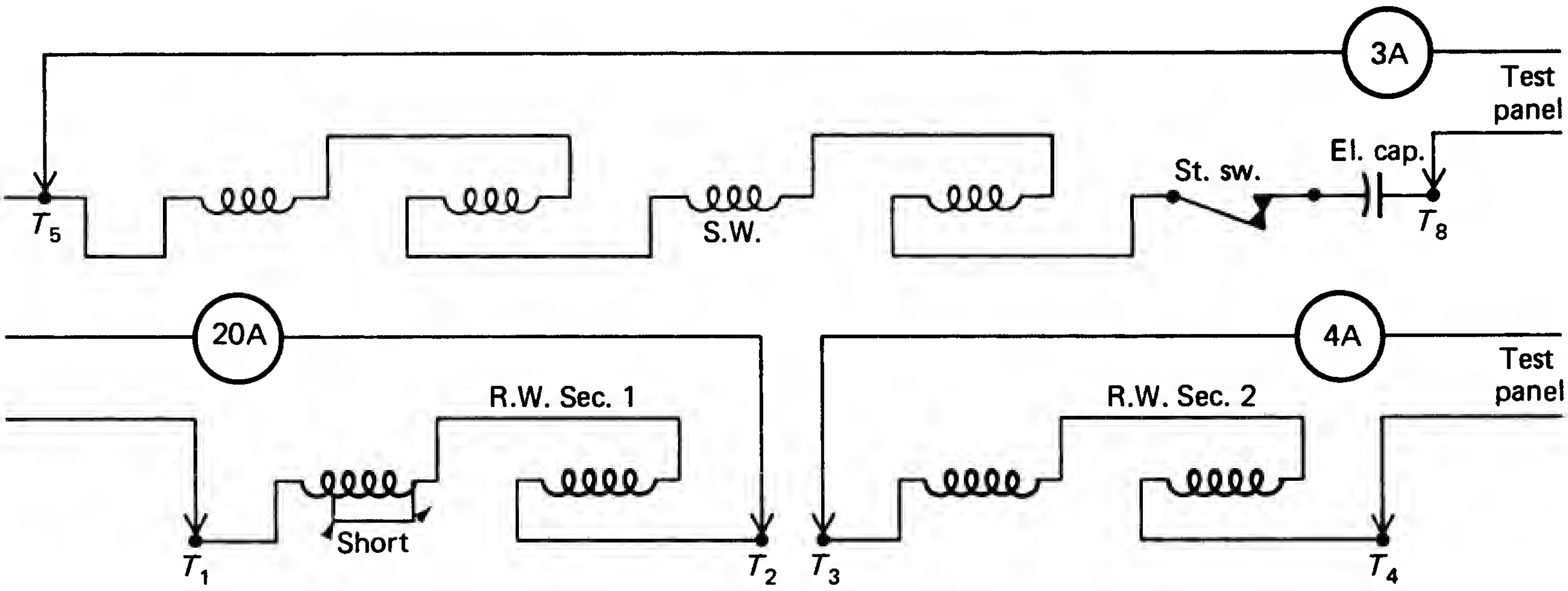


Fig. 1-211. Testing for the shorted circuit in a dual-voltage capacitor-start motor.

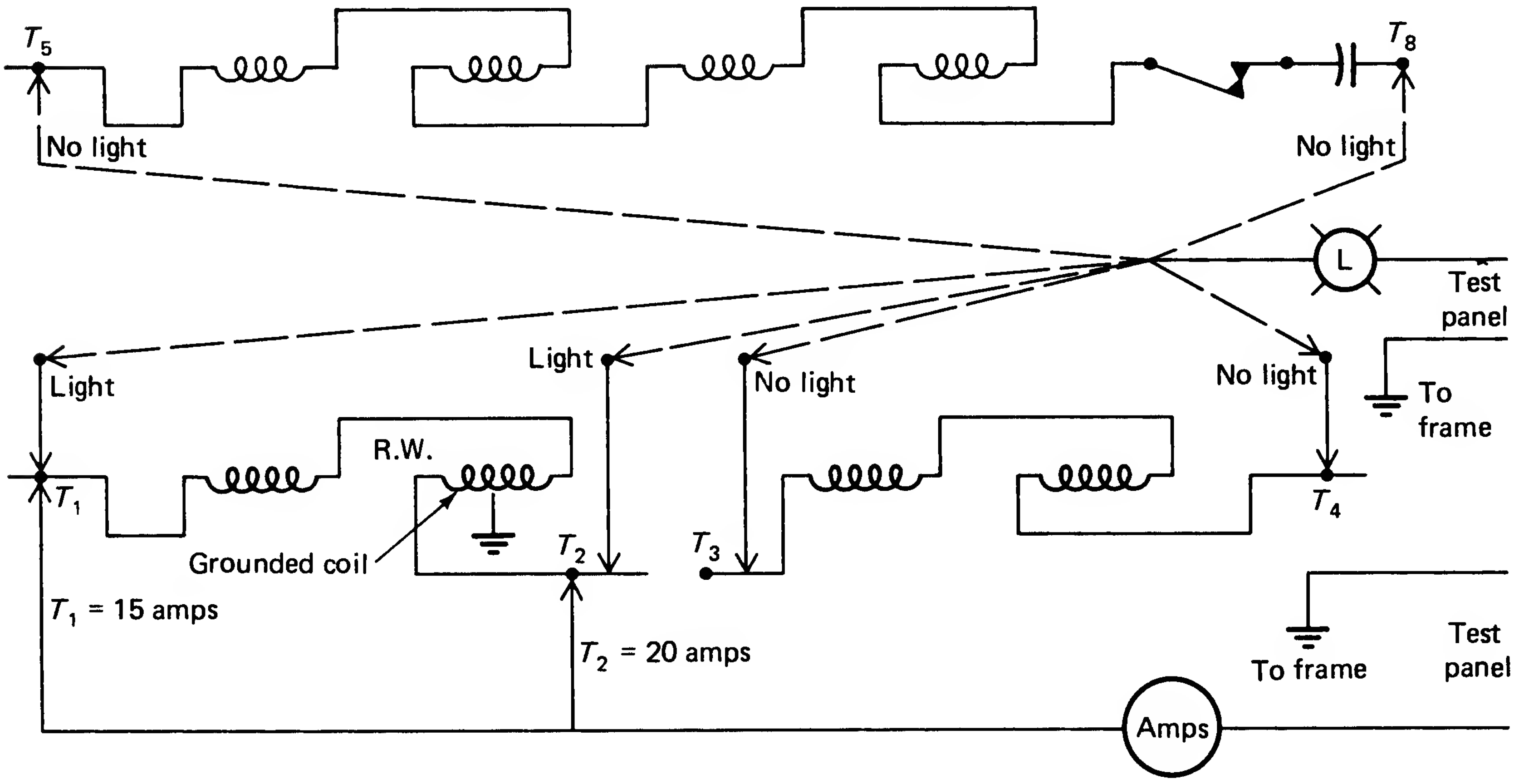


Fig. 1-212. First locate the grounded circuit with the test light, and then locate the grounded coil group with a limited current.

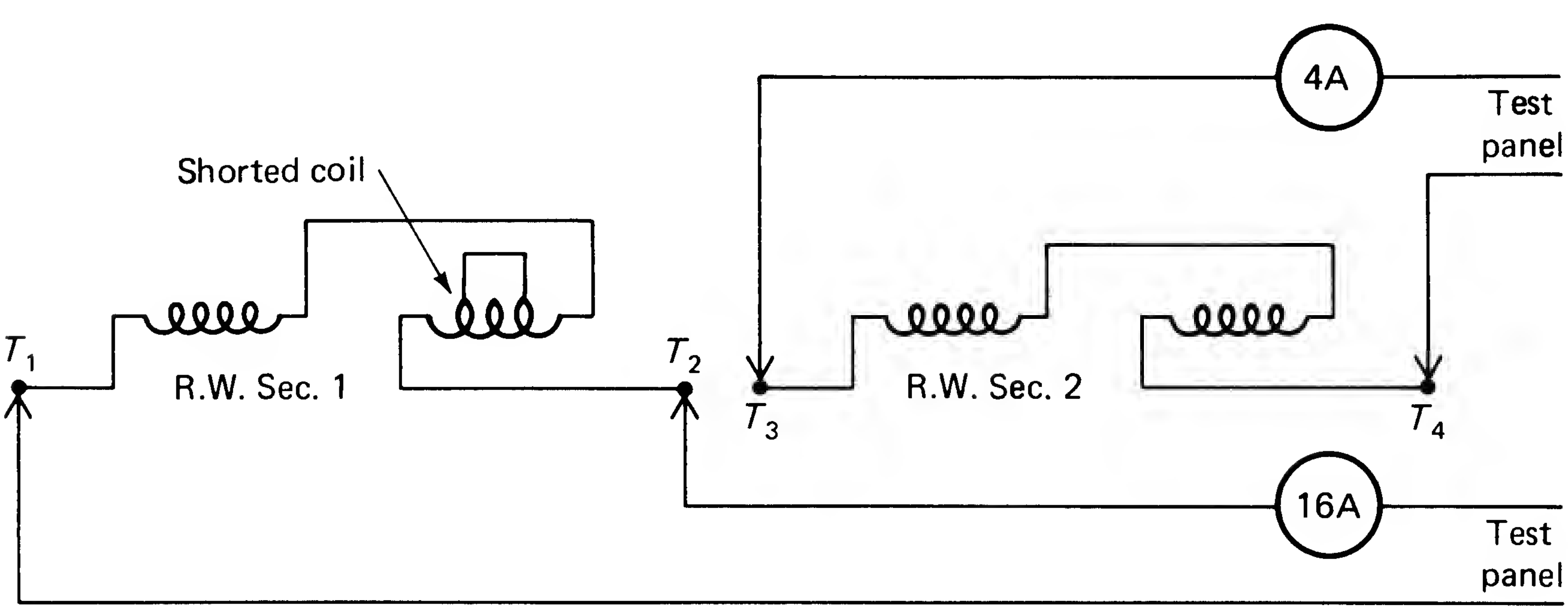


Fig. 1-213. Comparison test used to locate partially shorted section of dual-voltage run winding.

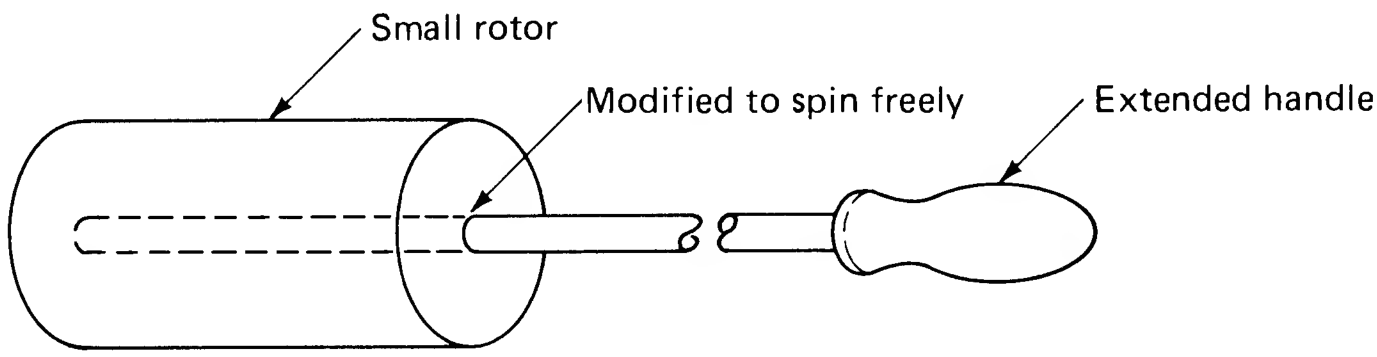
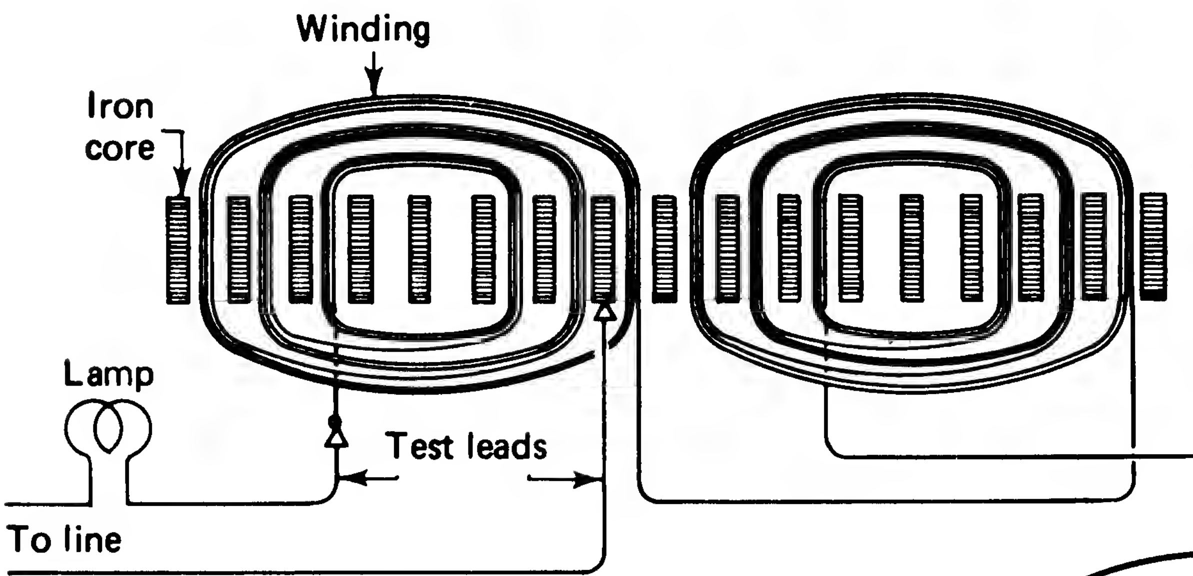


Fig. 1-214. Test rotor made from a small fan motor or a skeleton-type motor.



(A)

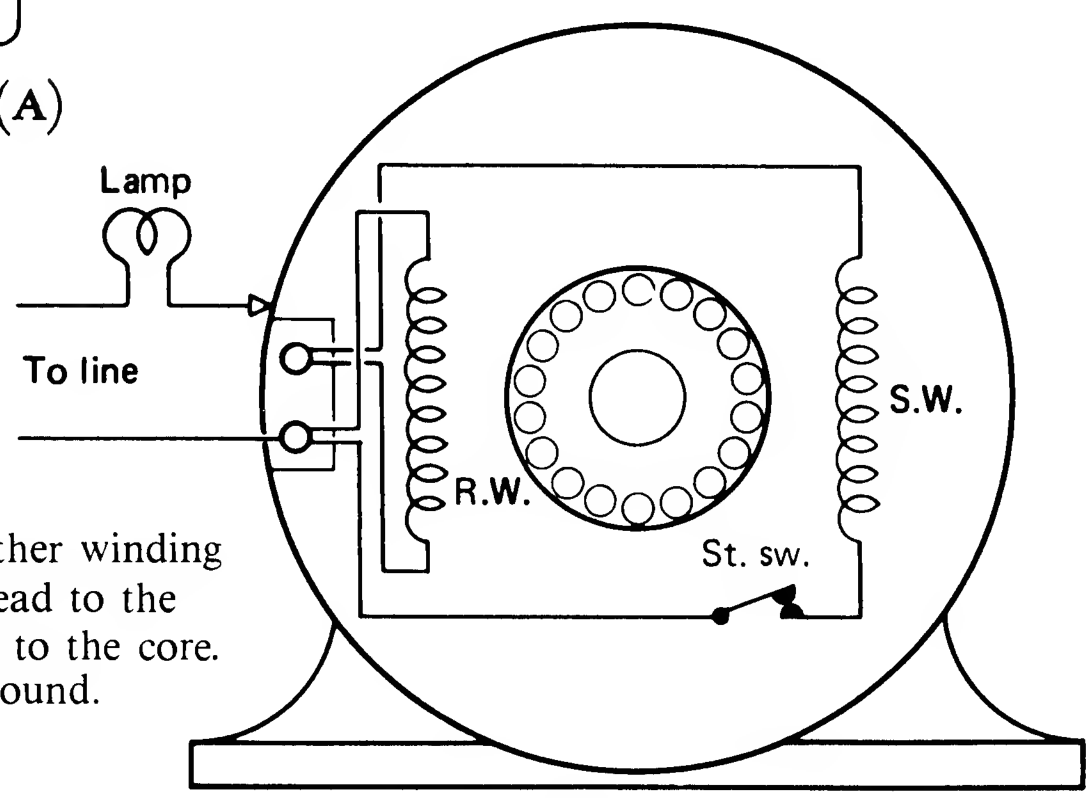


Fig. 1-215. To determine whether winding is grounded, connect one test lead to the winding and the other test lead to the core. The lighted lamp indicates a ground.

(B)

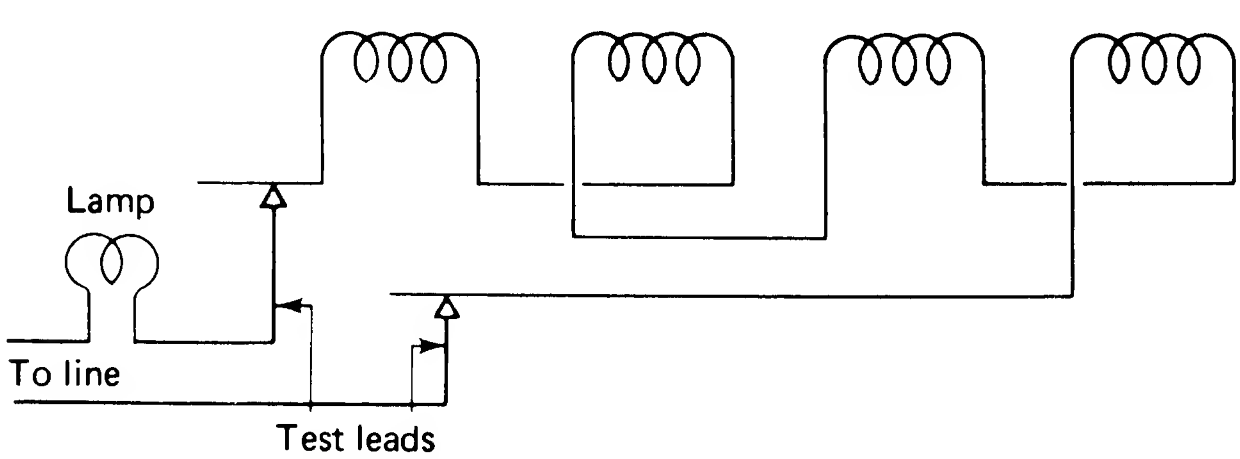


Fig. 1-216. A circuit for testing winding for opens.

Figures 1-214; 1-215; 1-216

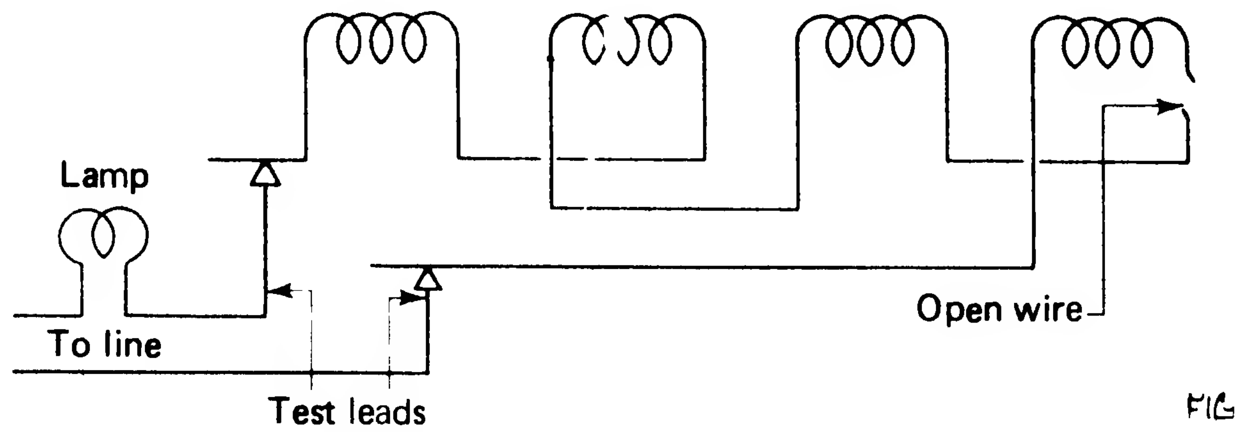


Fig. 1-217. The effect of a defective pole. If the circuit is open, the lamp will not light.

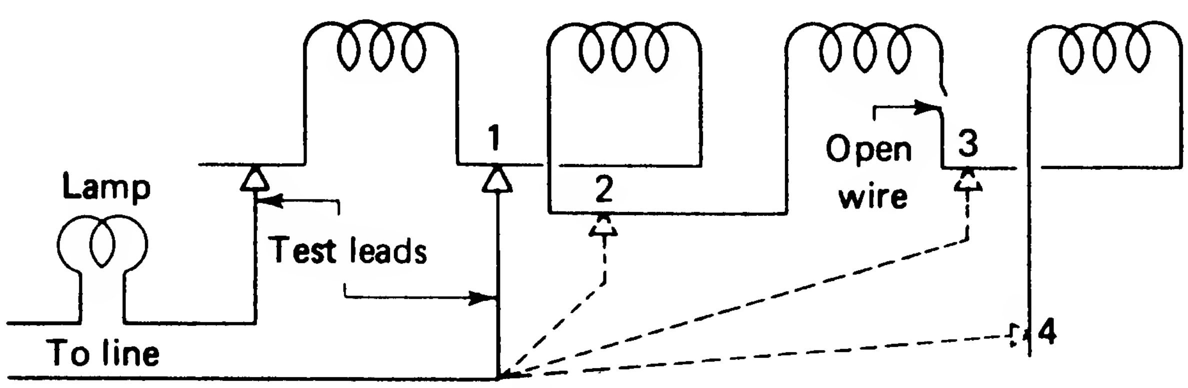


Fig. 1-218. The method of determining which pole is open-circuited.

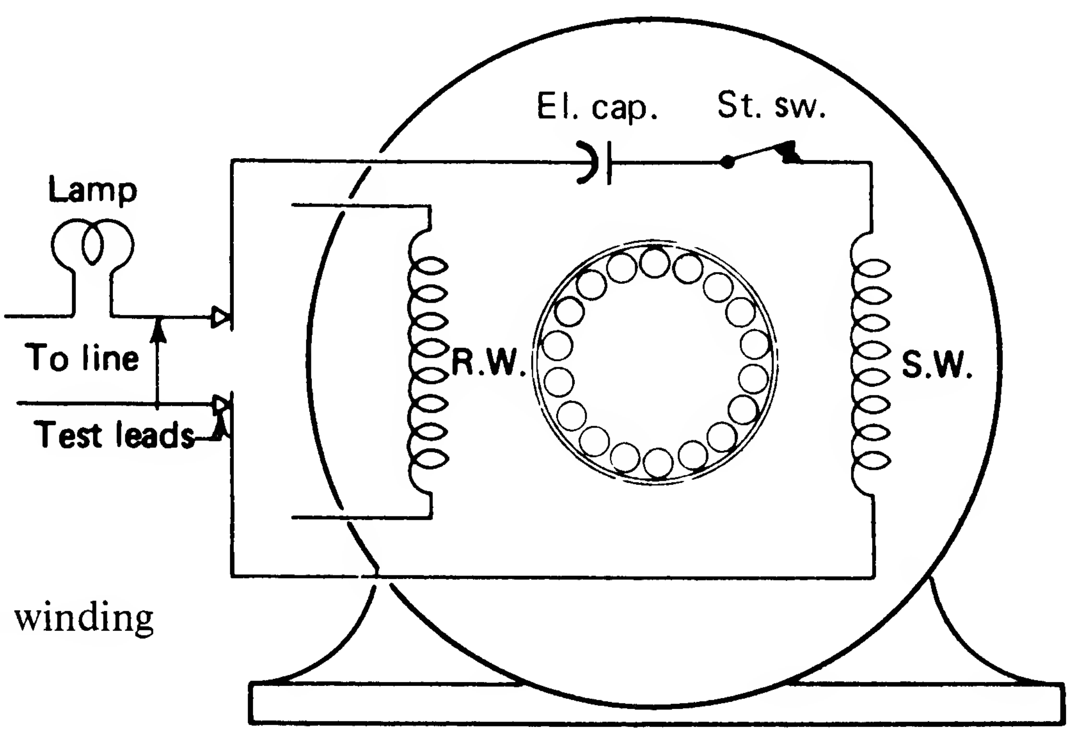


Fig. 1-219. Testing the start winding circuit for opens.

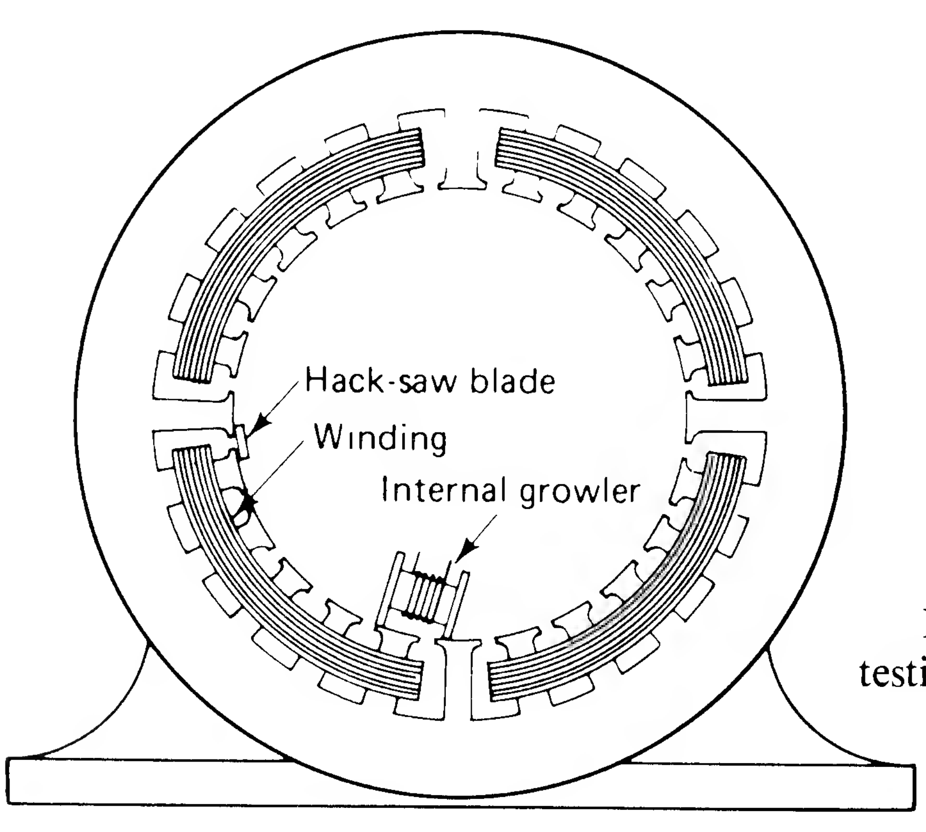


Fig. 1-220a. The growler method of testinng for shorts in the stator.

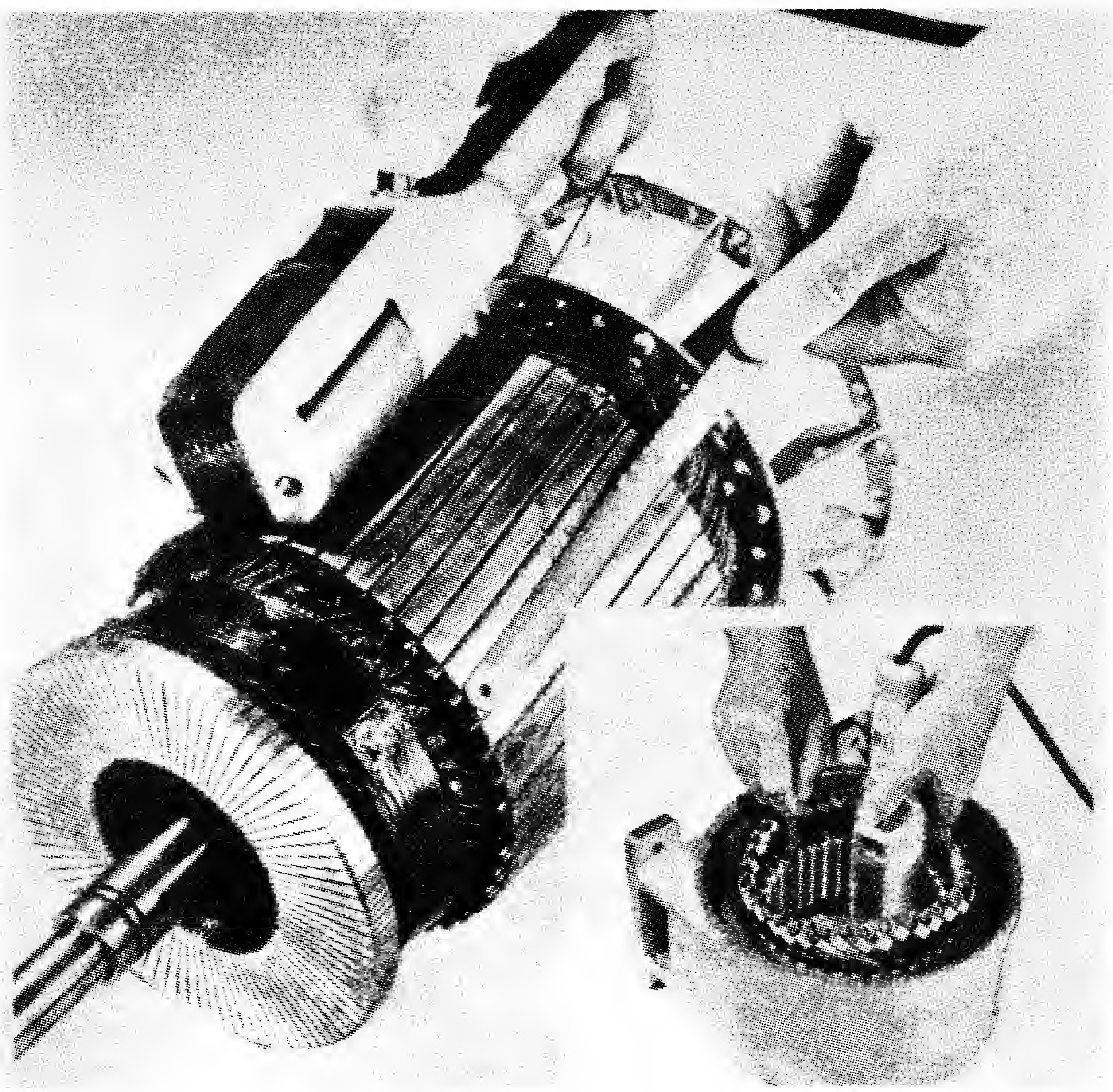


Fig. 1-220b. Internal, external growler. *(Crown Industrial Products)*

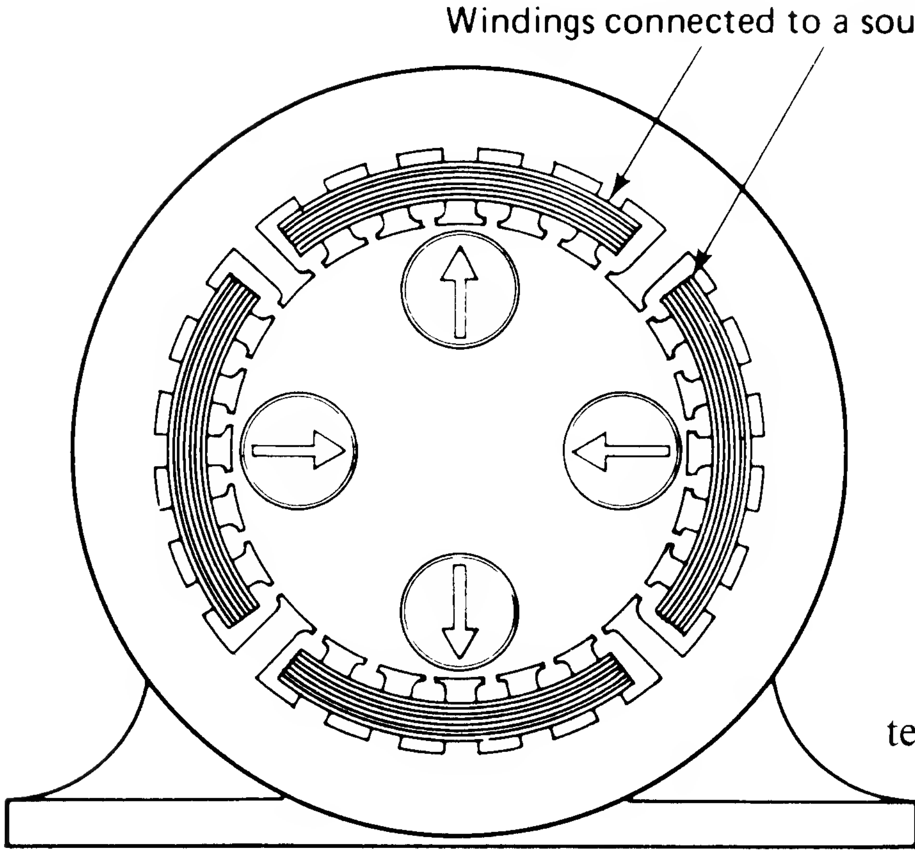


Fig. 1-221. The compass method of testing for reversed poles.

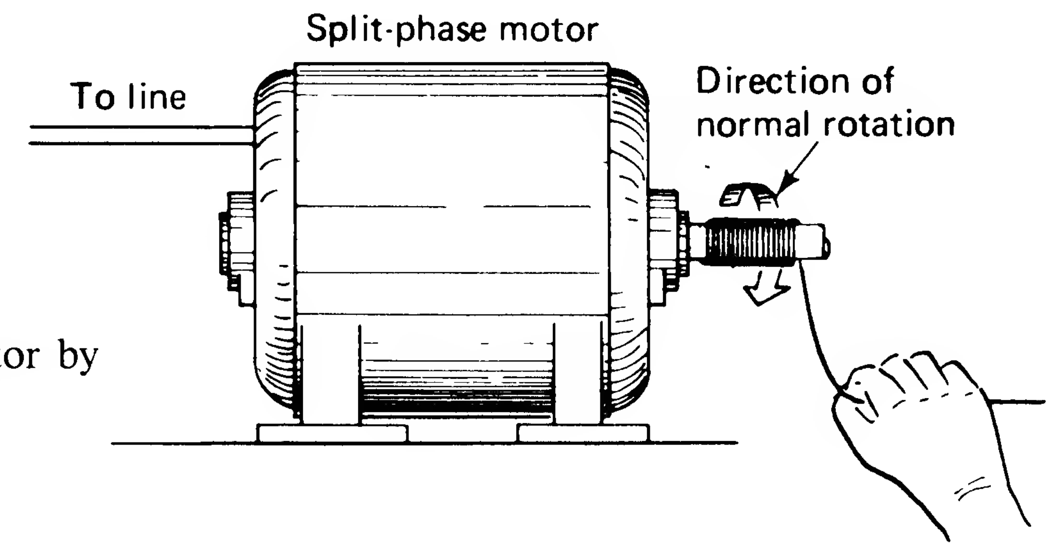


Fig. 1-222. Starting the motor by mechanical means.

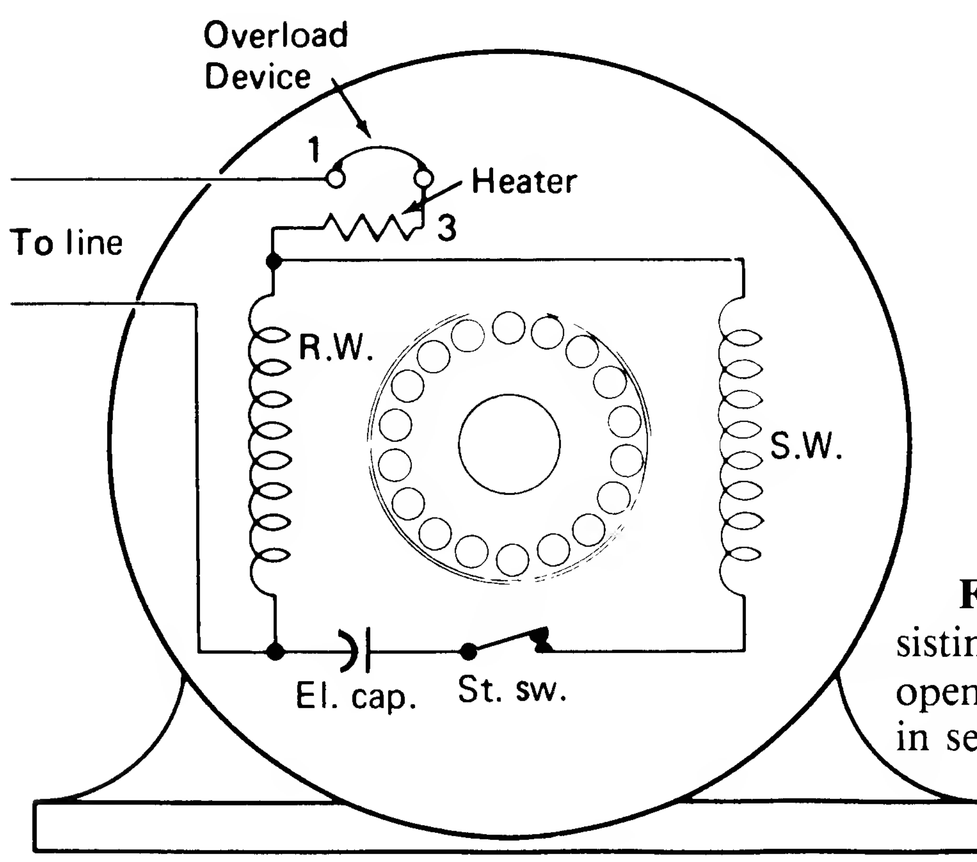


Fig. 1-223. An overload device, consisting of a bimetallic element that will open circuit on overload. It is connected in series with the line.

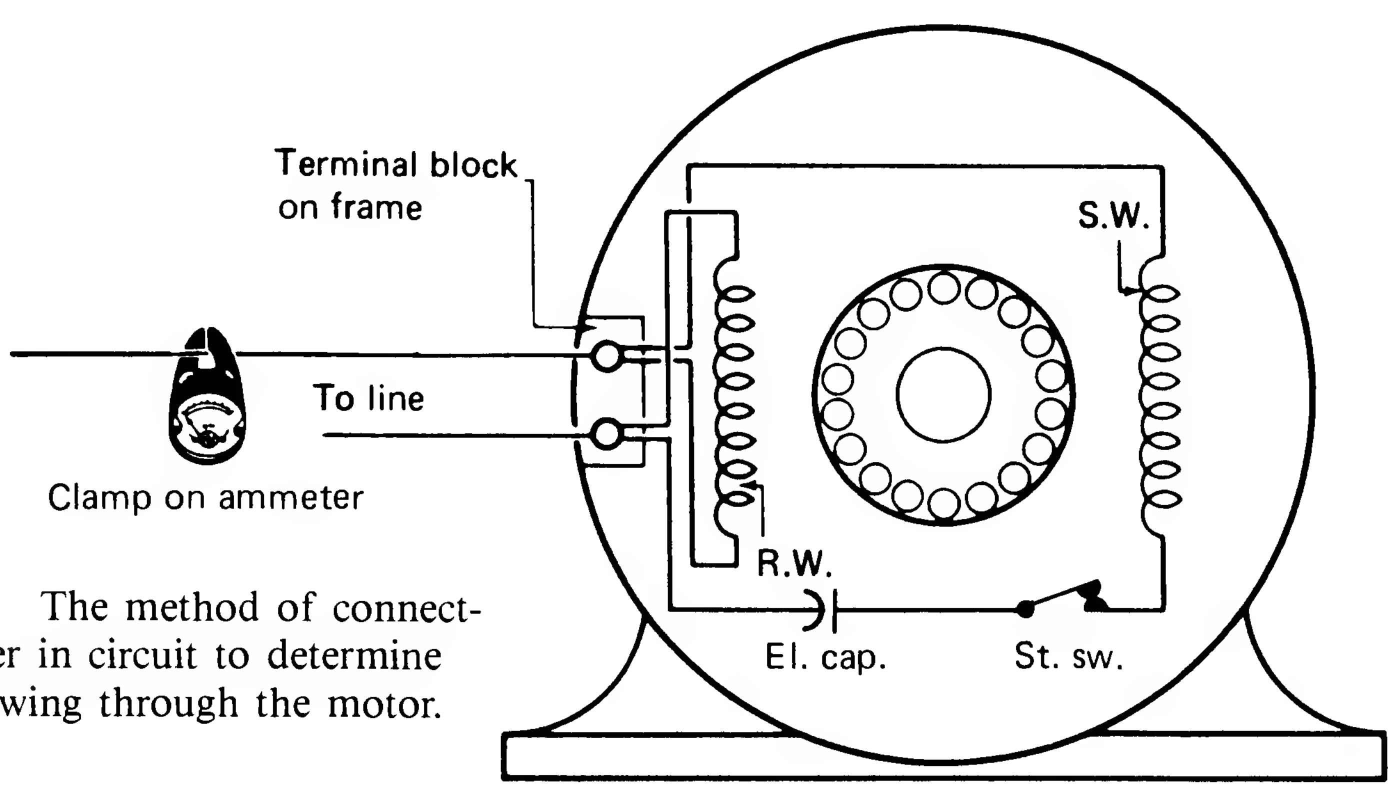


Fig. 1-224. The method of connecting an ammeter in circuit to determine the current flowing through the motor.

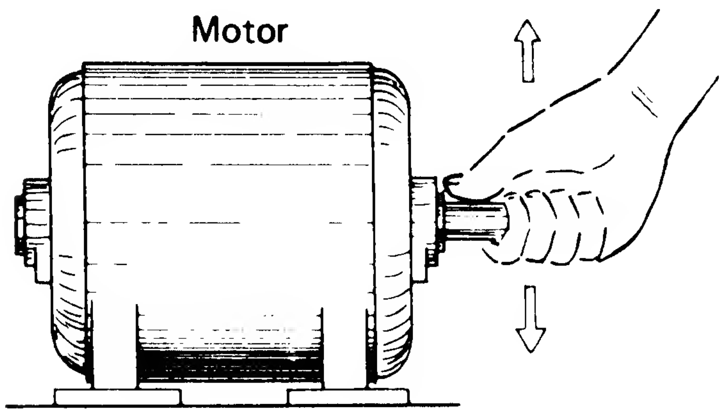


Fig. 1-225. The bearings are tested by trying to move the shaft vertically.

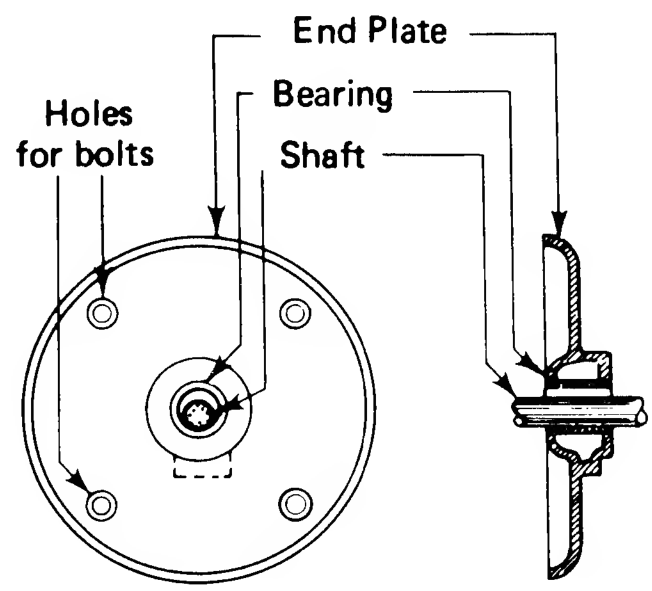


Fig. 1-226. If the shaft can be moved vertically, it indicates a worn bearing or worn rotor shaft.

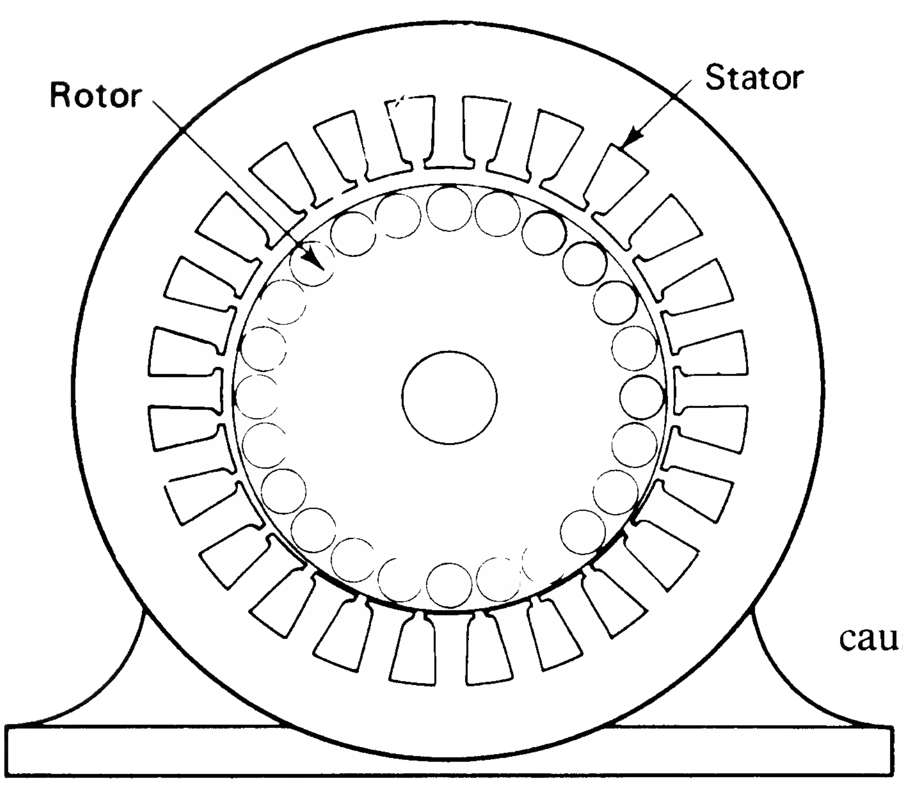


Fig. 1-227. A worn bearing may cause the rotor to rub on the stator core.

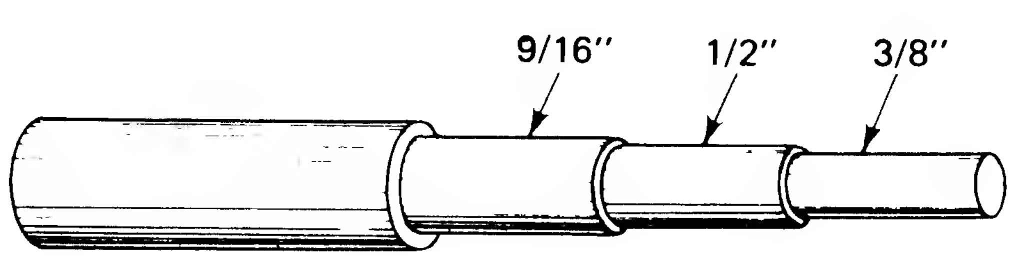


Fig. 1-228. The tool used for forcing bearings out of end plates.

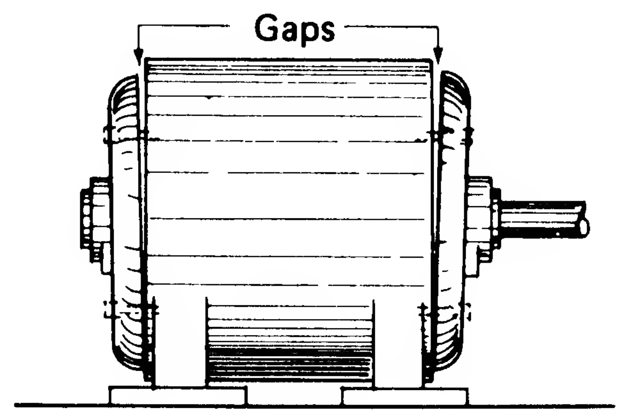


Fig. 1-229. A motor showing end plates not mounted properly. This prevents the rotor from turning. Use a mallet to tap plates into position.

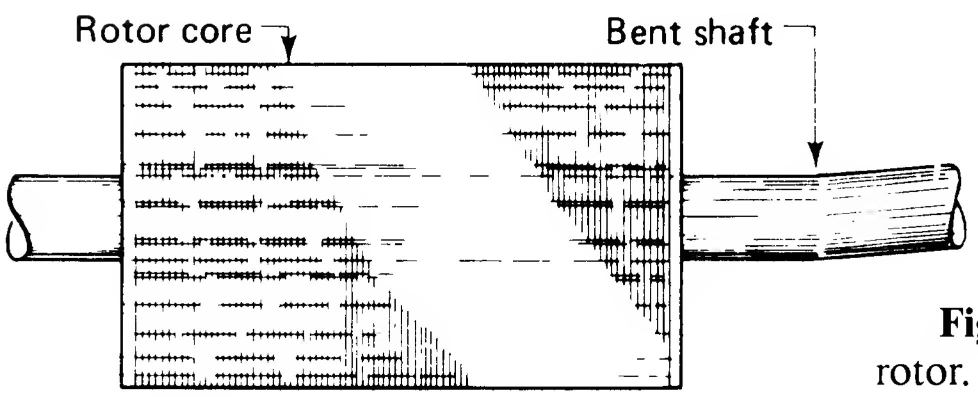


Fig. 1-230. The bent shaft of a rotor.

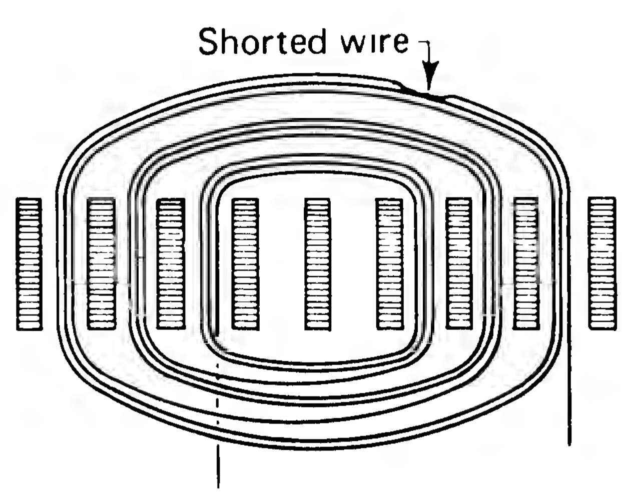


Fig. 1-231. Two turns making electrical contact.

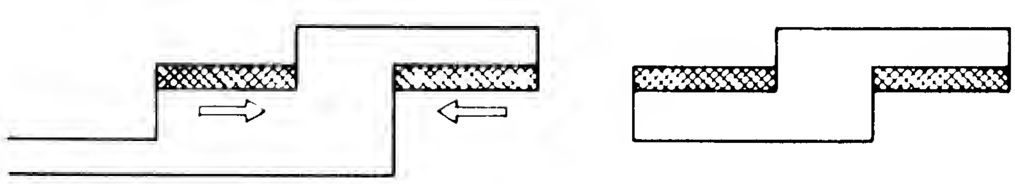


Fig. 1-232. A connection mistake often made by beginners.

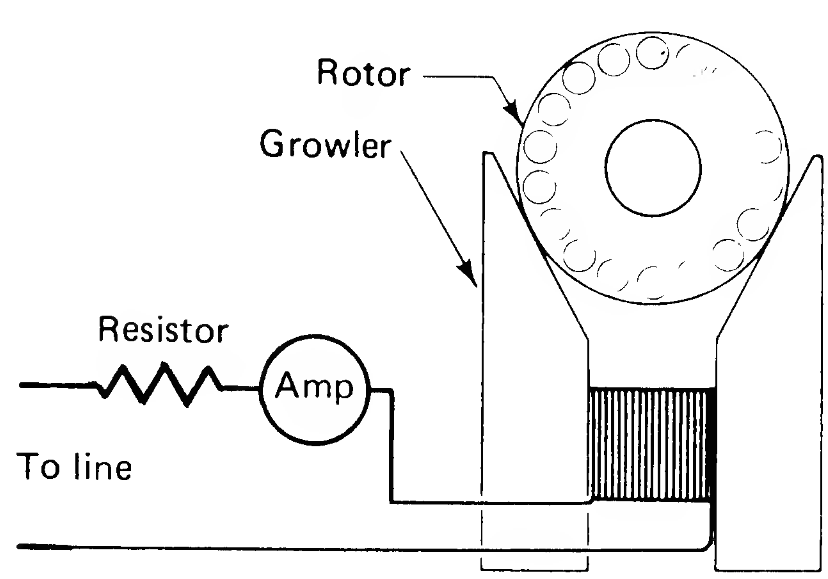


Fig. 1-233. The rotor under test placed between the open ends of the growler core.

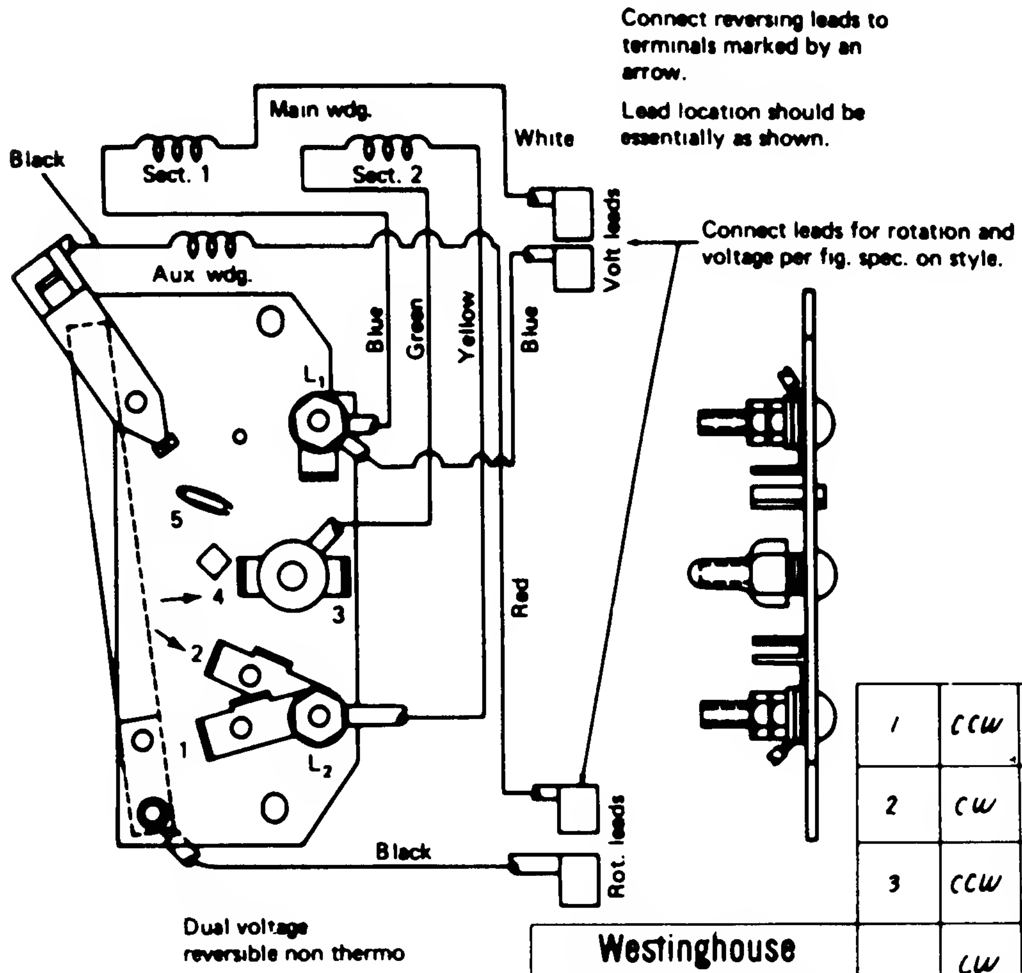


FIG	ROT	ROT CONN	VOLT	VOLT CONN
1	CCW	BLACK → 2 RED → 4	230	WHITE → 1 3 BLUE → 5
2	CW	RED → 2 BLACK → 4	230	WHITE → 1 3 BLUE → 5
3	CCW	BLACK → 2 RED → 4	115	WHITE → 1 BLUE → 3 5
	CW	RED → 2 BLACK → 4	115	WHITE → 1 BLUE → 3 5

Westinghouse
ELECTRIC CORP LIMA WKS
LIMA OHIO USA
SMALL MOTOR DIVISION

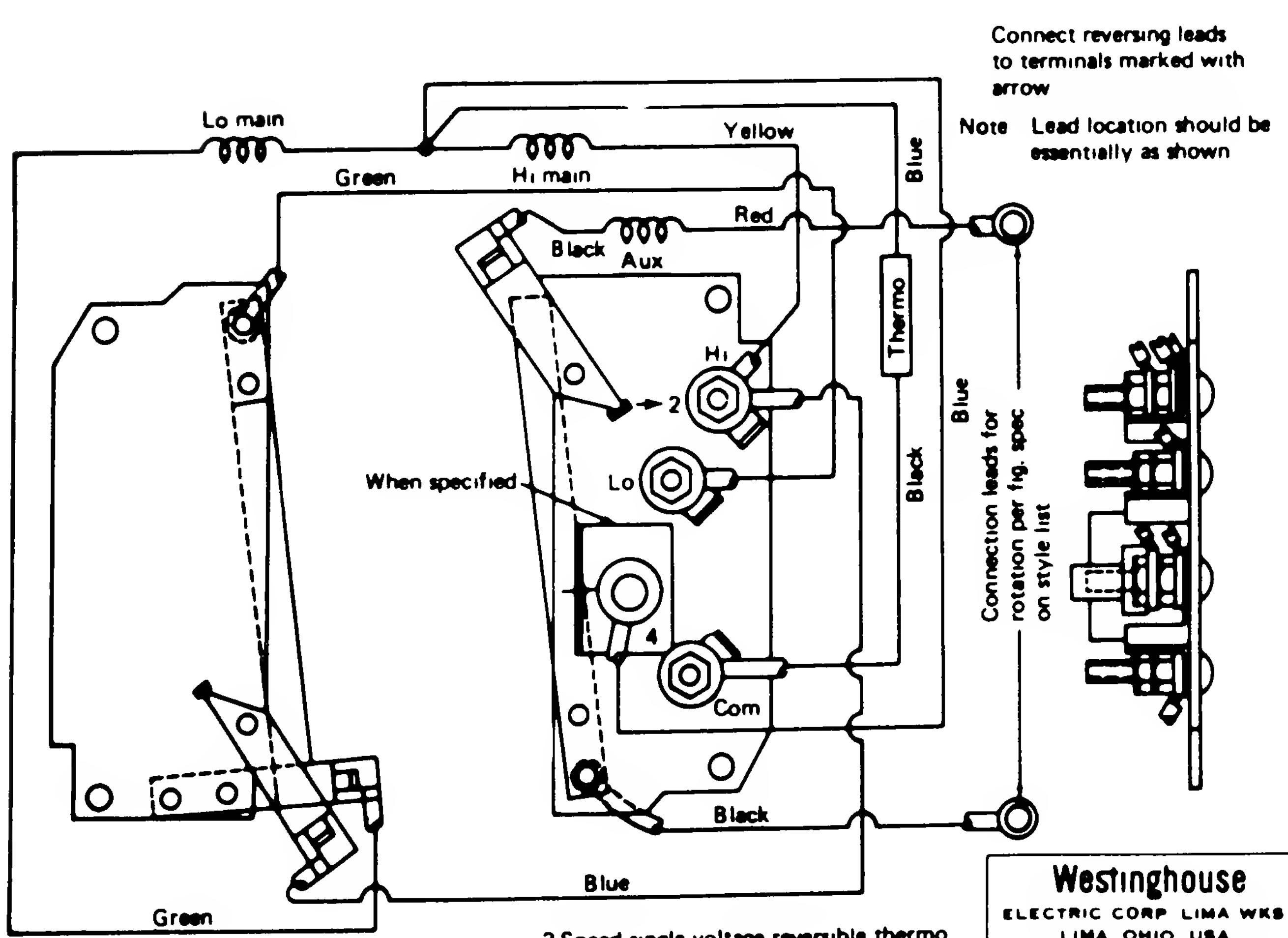
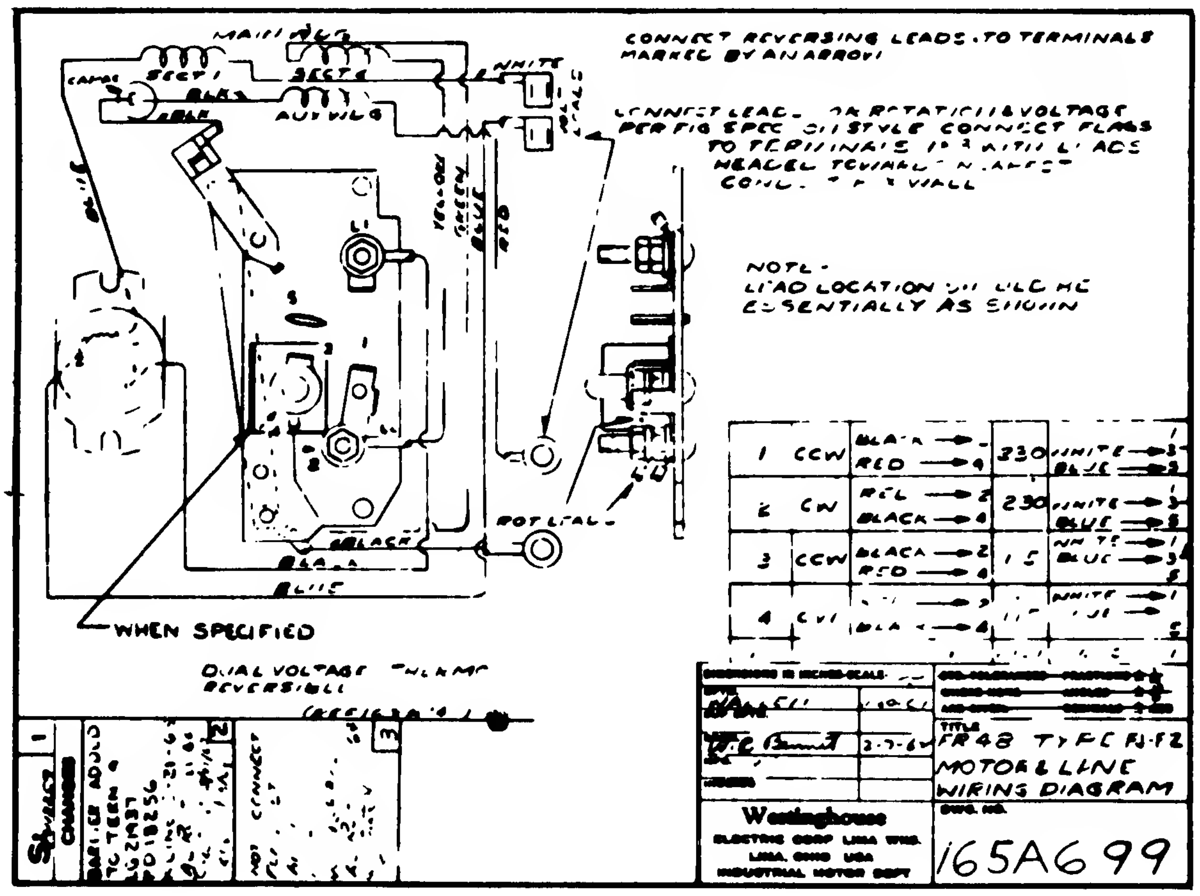
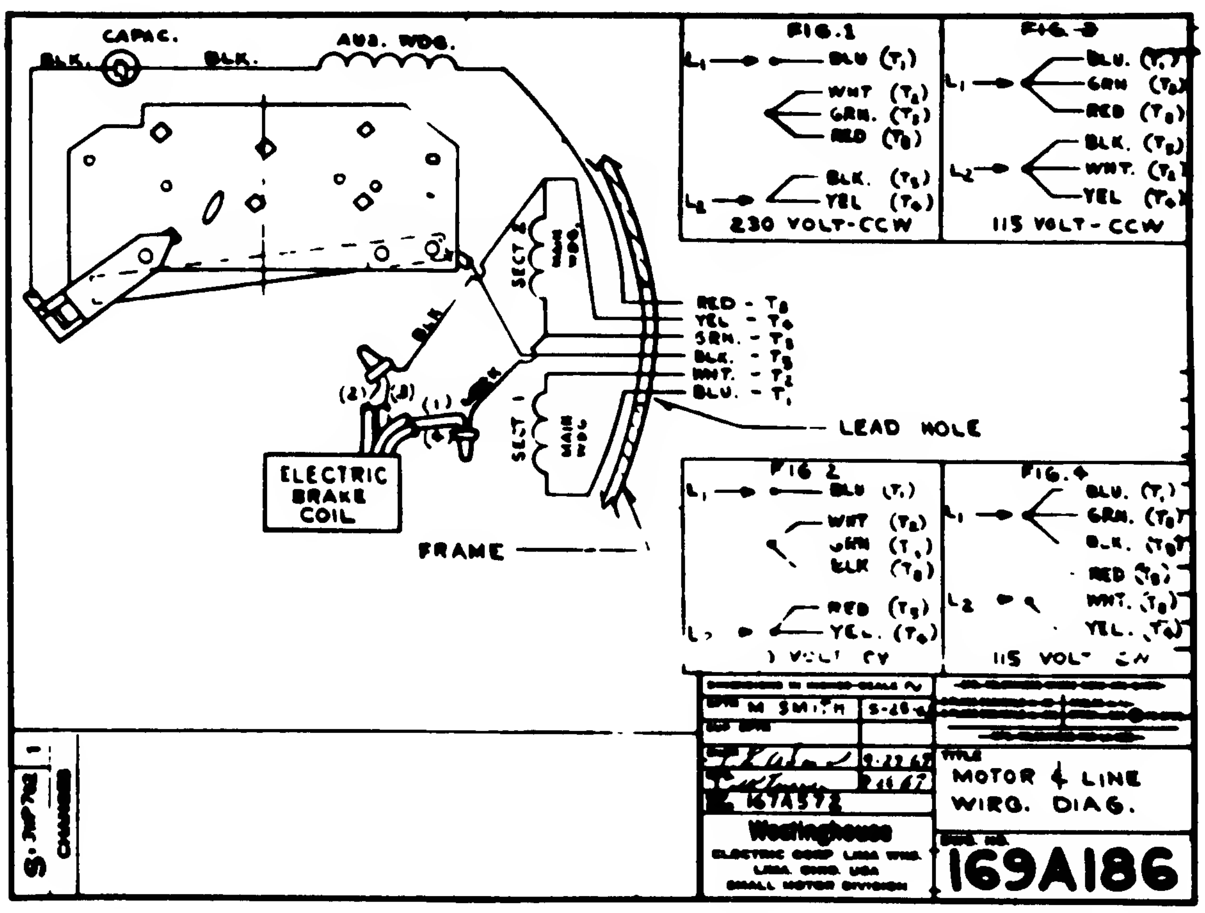


FIG	ROT	CONNECT
2	CW	RED → 2 BLK → 4
1	CCW	BLK → 2 RED → 4

Westinghouse
ELECTRIC CORP LIMA WKS
LIMA OHIO USA
SMALL MOTOR DIVISION

Fig. 1–234. Miscellaneous diagrams.





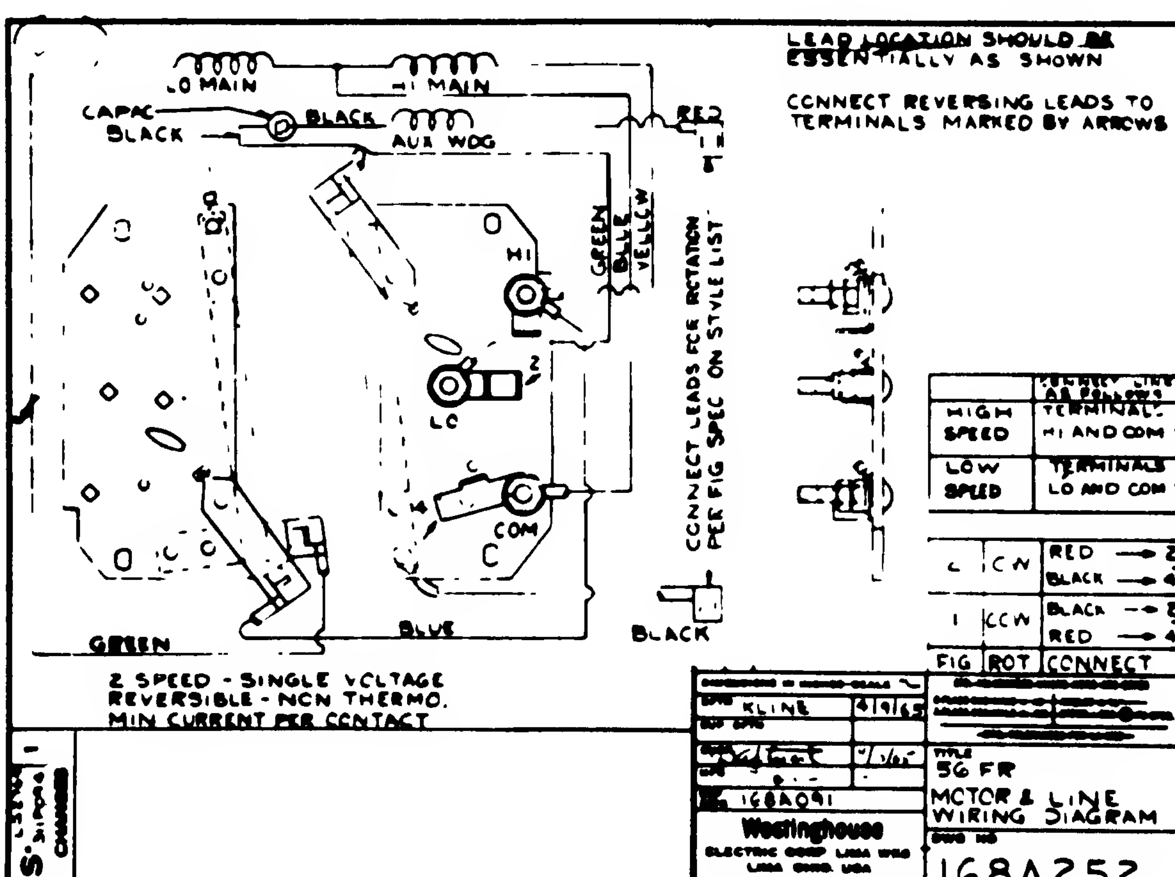


Fig. 1–234. Miscellaneous diagrams (*continued*).

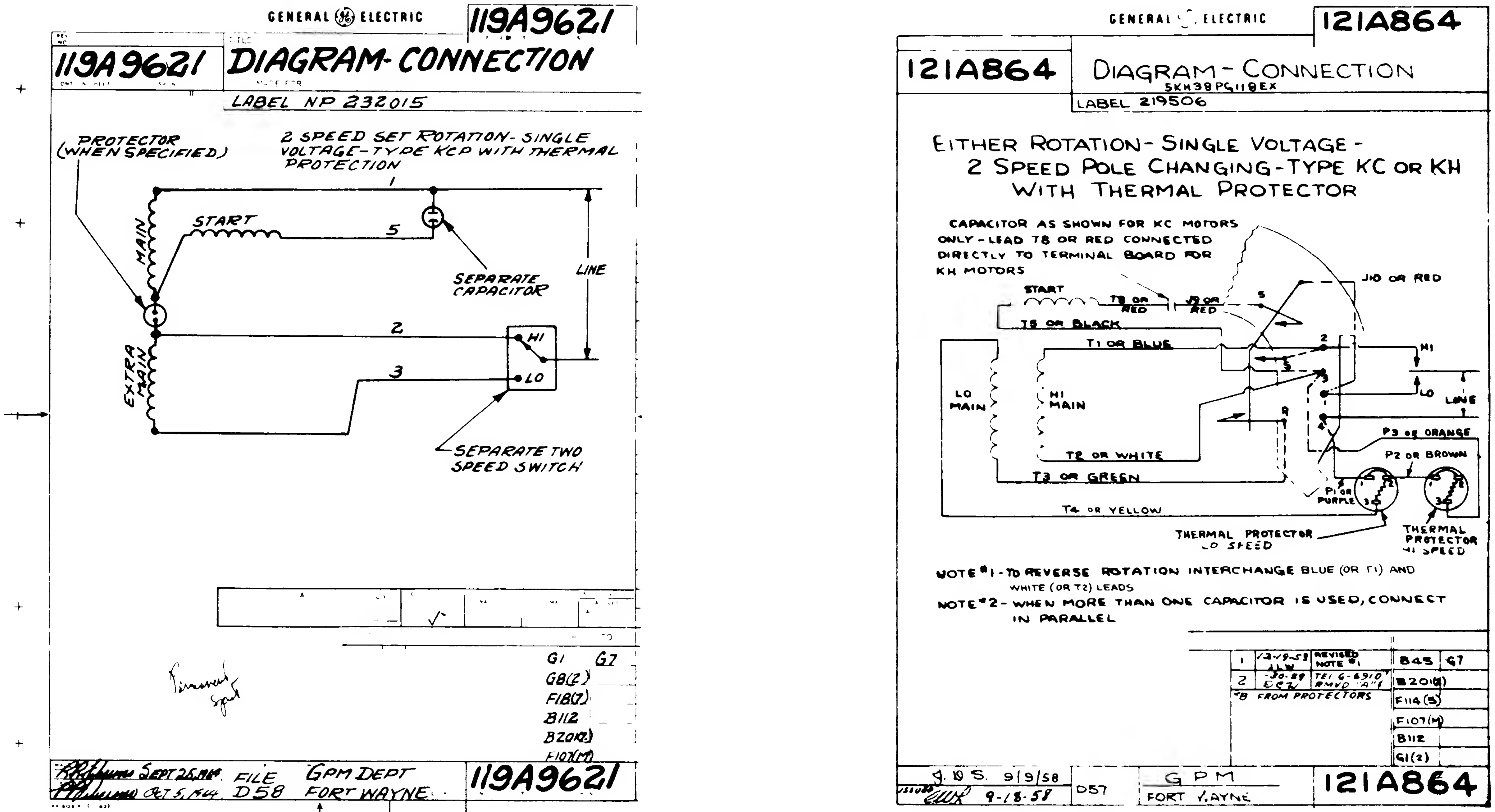
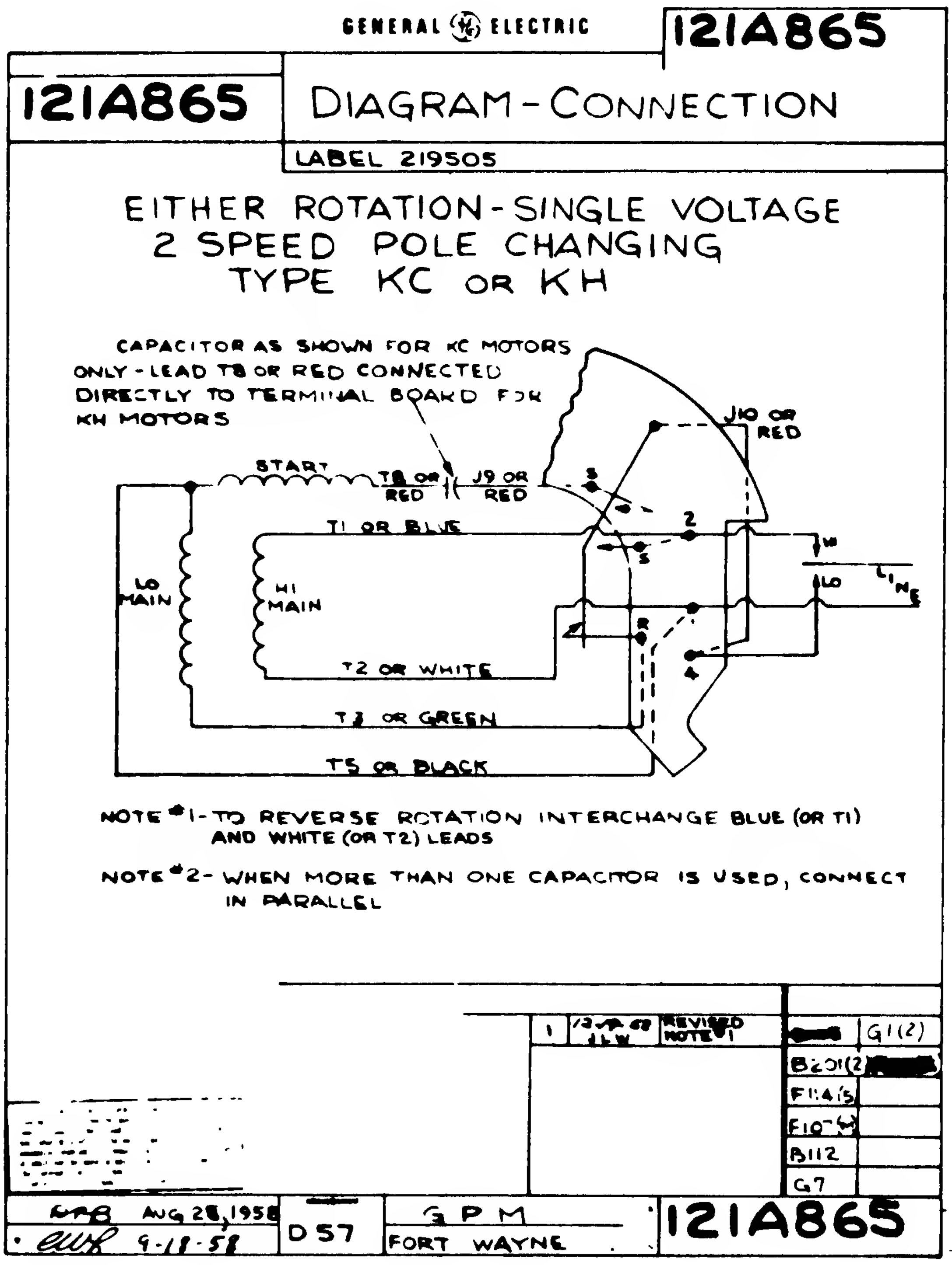


Fig. 1–235. Miscellaneous diagrams (*continued*).



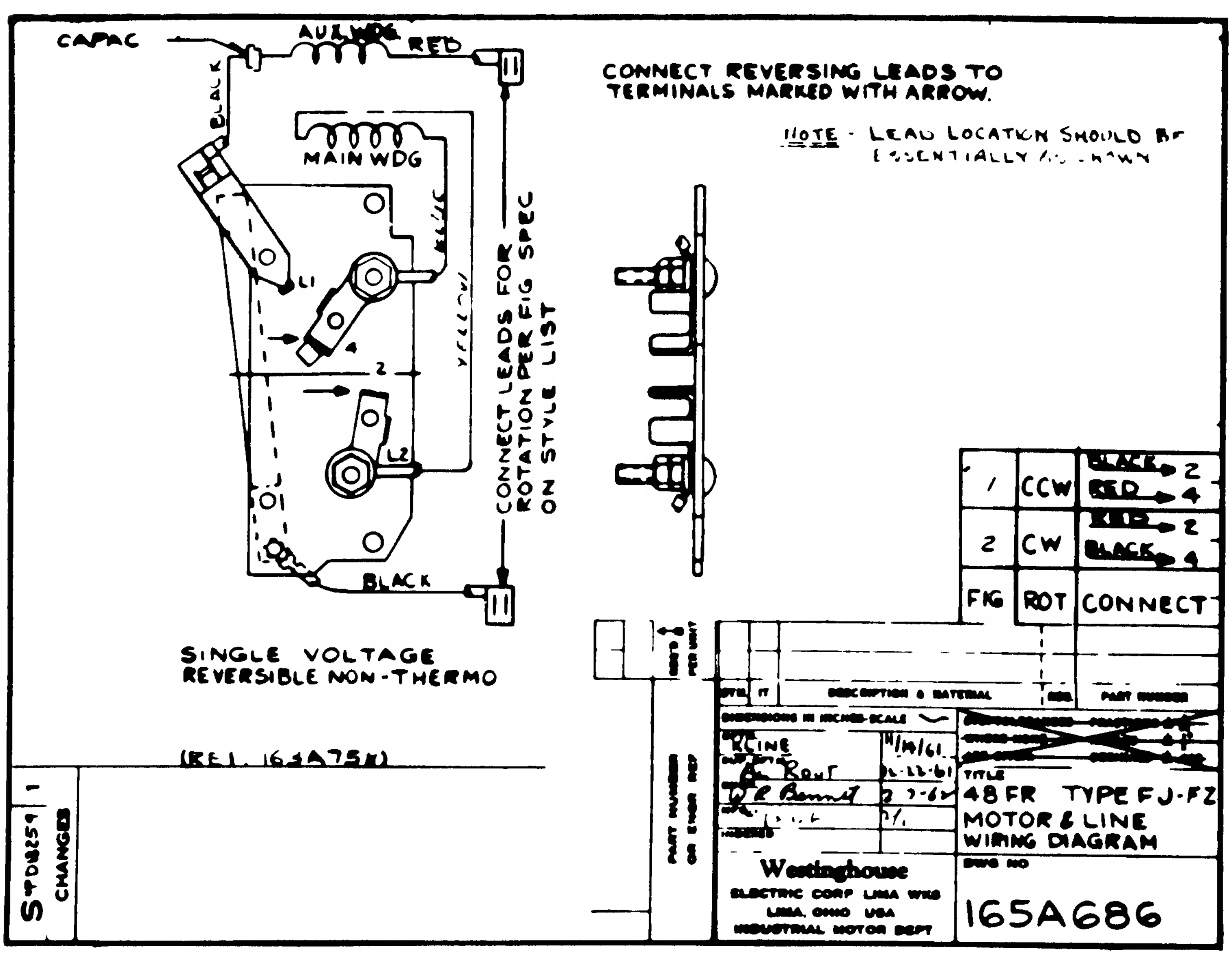


Fig. 1-235. Miscellaneous diagrams (*continued*).

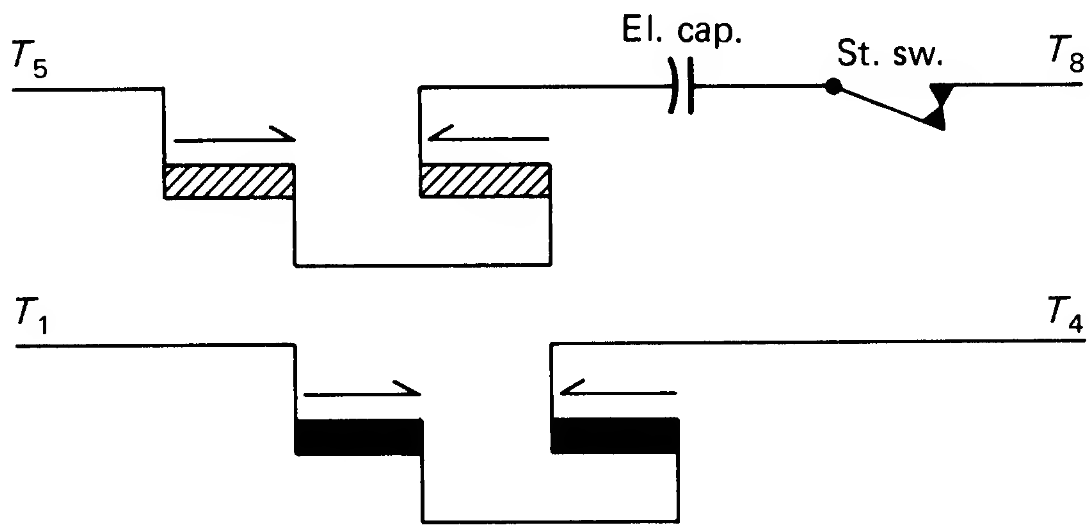


Fig. 1-236. A two-pole, capacitor motor with a one-circuit start and a one-circuit run winding.

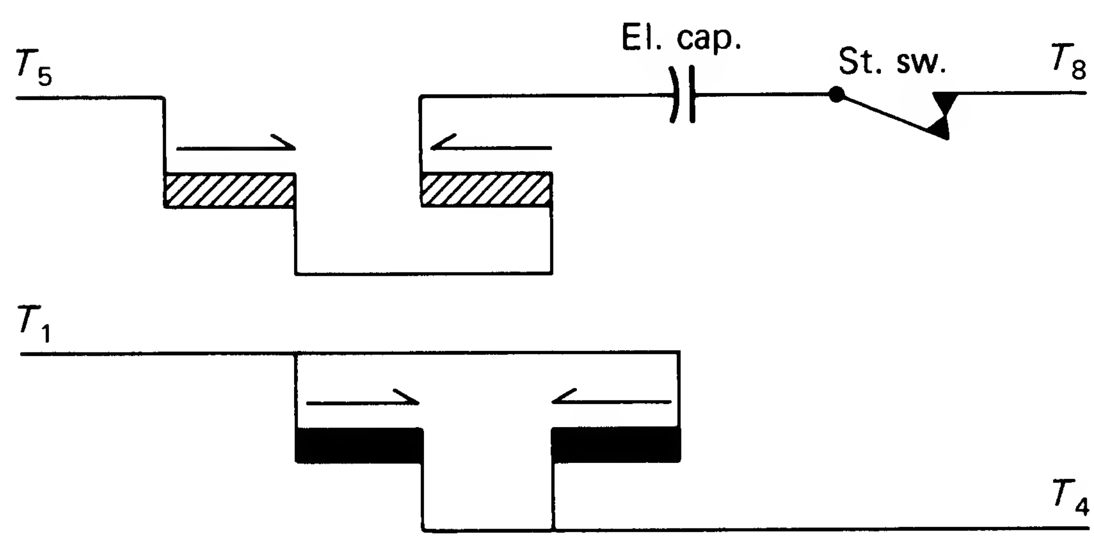


Fig. 1-237. A two-pole, capacitor start motor with a one-circuit start and a two-circuit run winding.

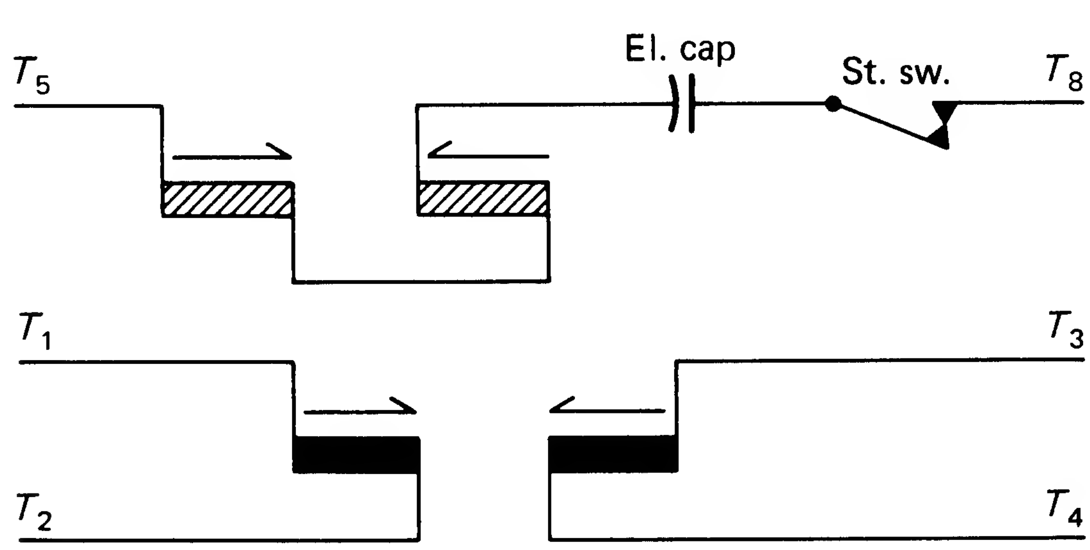


Fig. 1-238. A two-pole, capacitor start motor with a one-circuit start and a one- and two-circuit run winding.

CHAPTER 2

Repulsion-type Motors

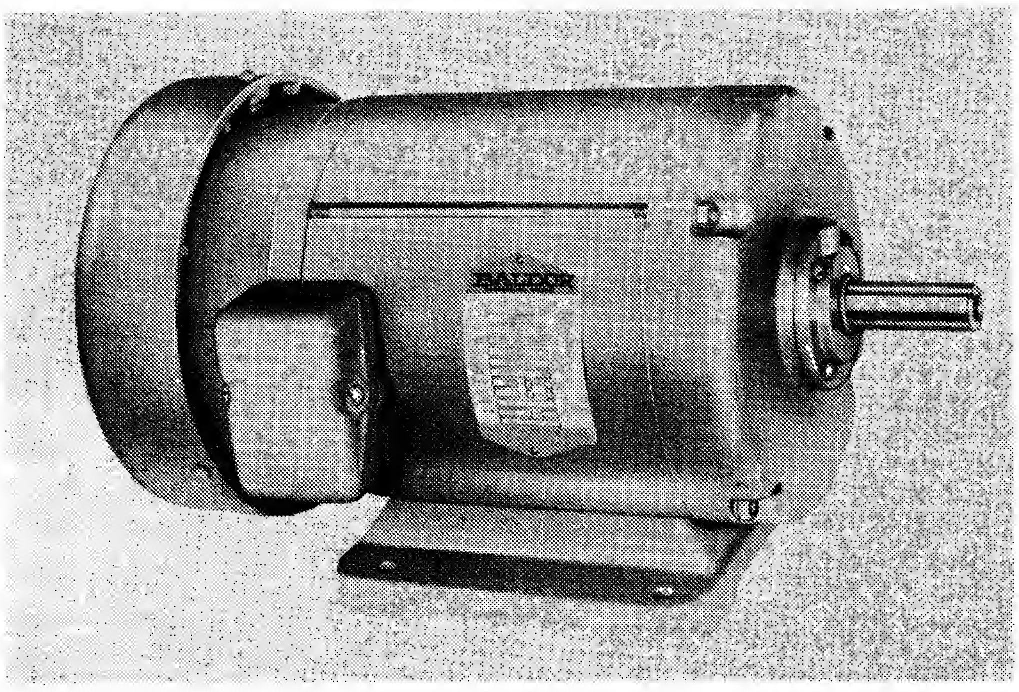


Fig. 2-1. A repulsion-start induction motor. *(Wagner Electric Co.)*

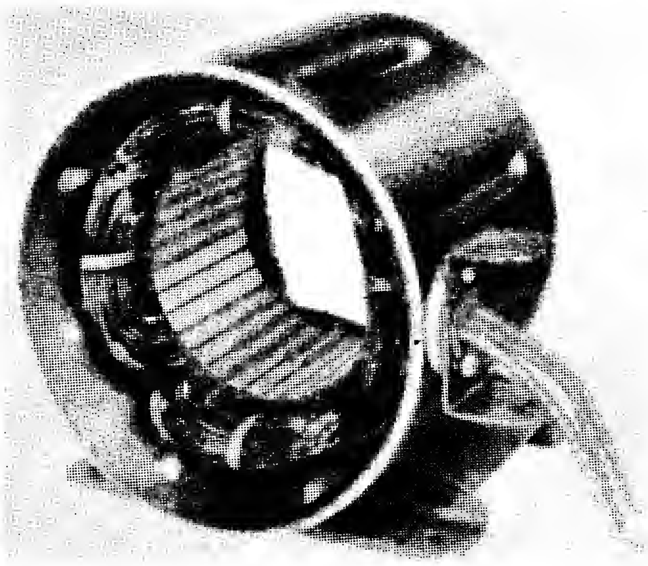


Fig. 2-2. Stator and winding of a repulsion-start, induction motor. *(Wagner Electric Co.)*

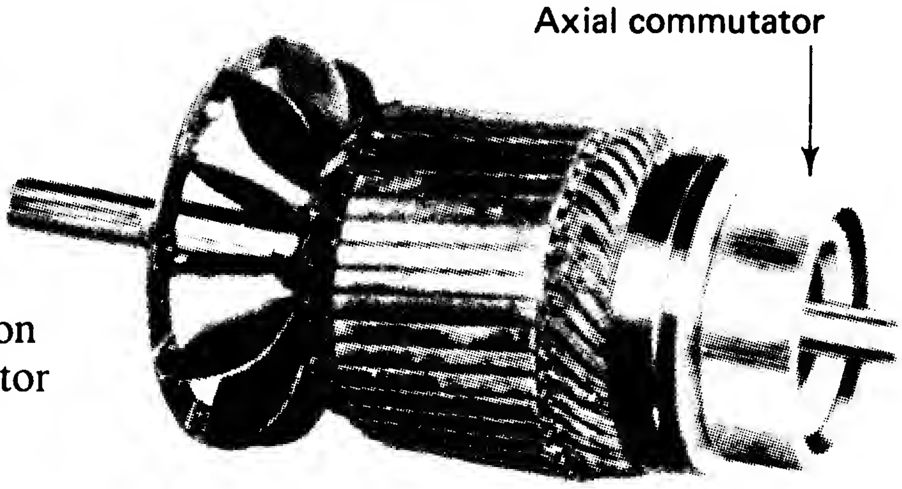


Fig. 2-3. The rotor of a repulsion induction motor. The axial commutator has bars parallel to the shaft.

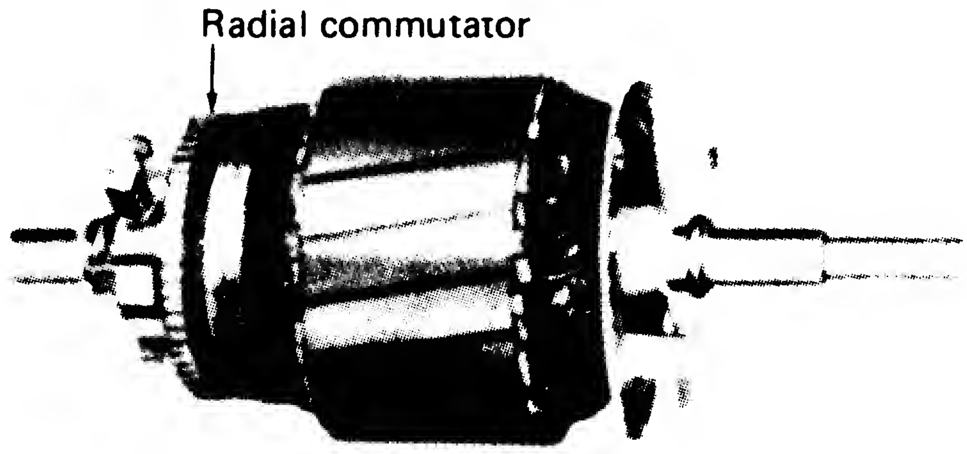


Fig. 2–4. A rotor having a radial commutator with bars perpendicular to the shaft. *(Wagner Electric Company)*

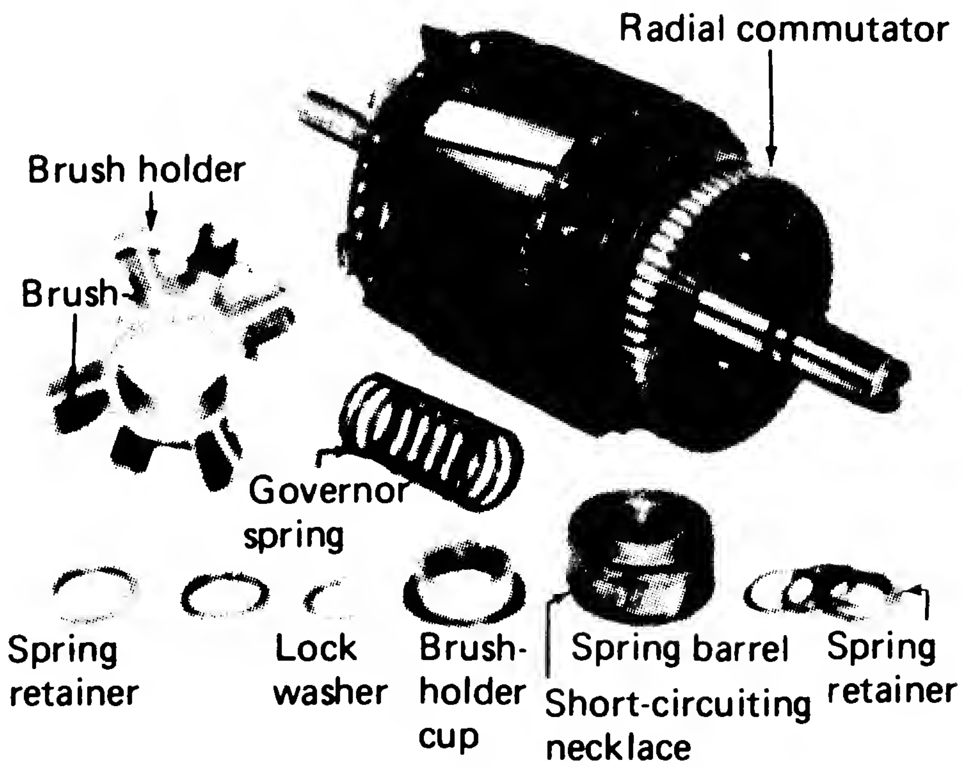


Fig. 2–5. A partly dismantled rotor and parts of the centrifugal mechanism. *(Wagner Electric Company)*

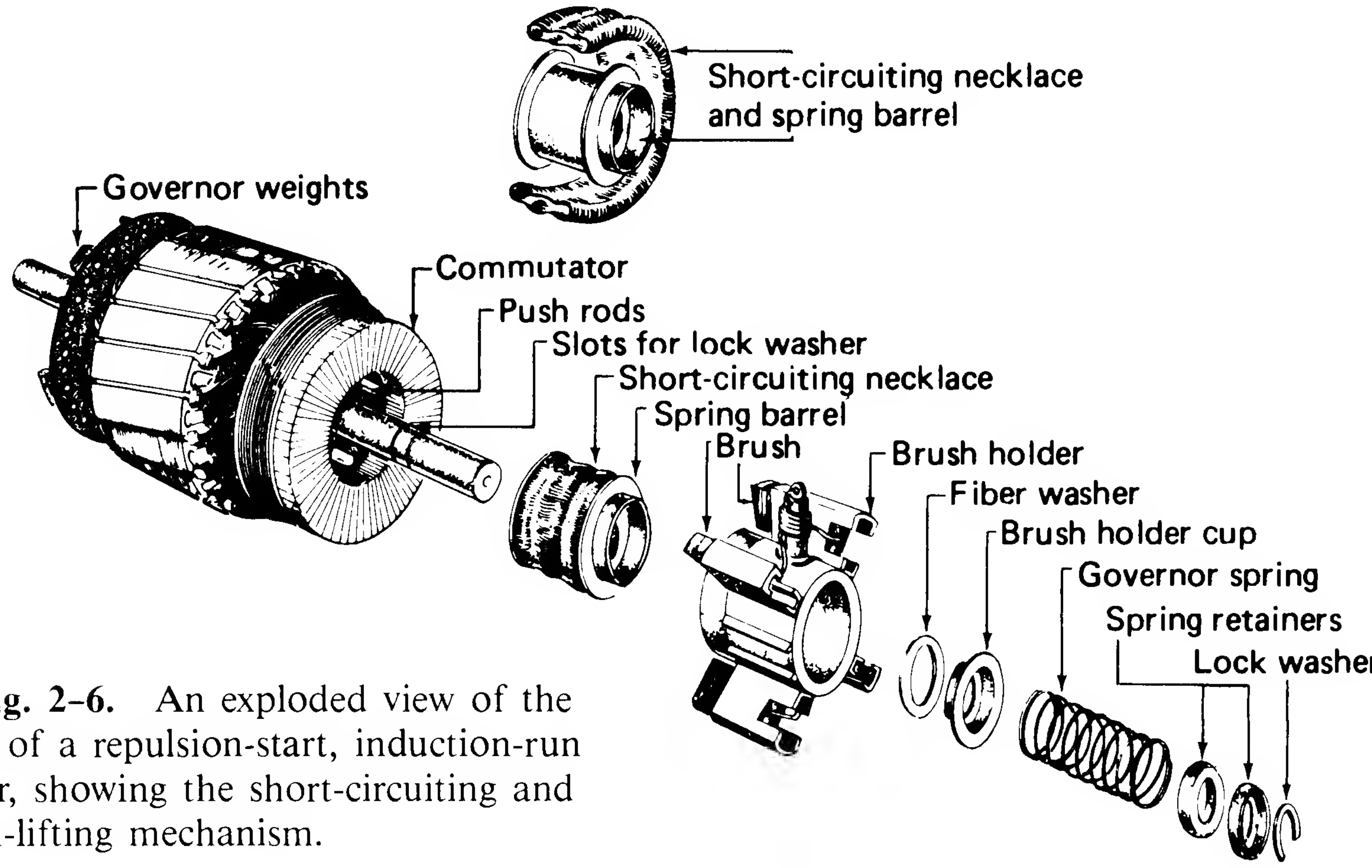


Fig. 2–6. An exploded view of the rotor of a repulsion-start, induction-run motor, showing the short-circuiting and brush-lifting mechanism.

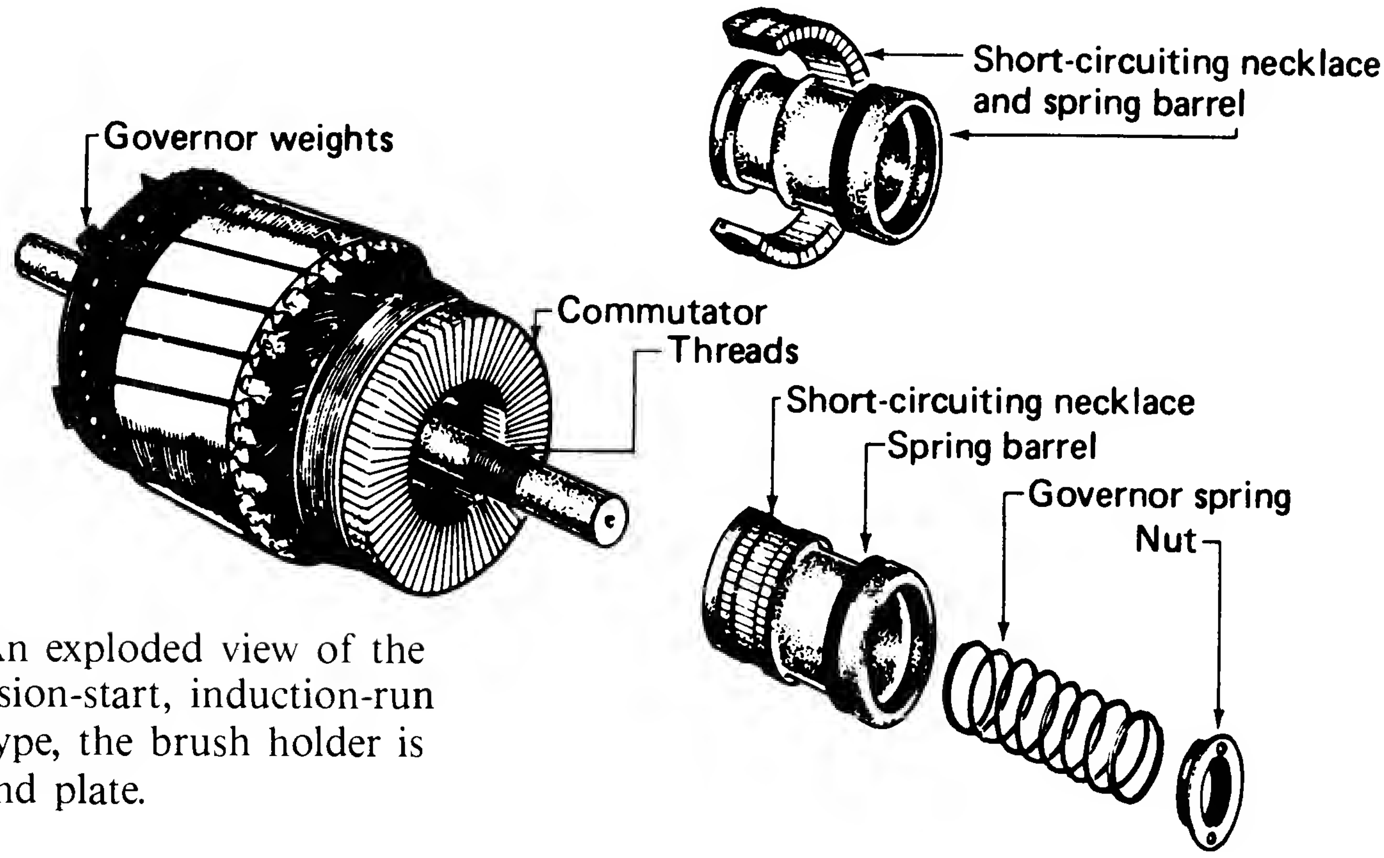


Fig. 2-7. An exploded view of the rotor of a repulsion-start, induction-run motor. In this type, the brush holder is located in the end plate.

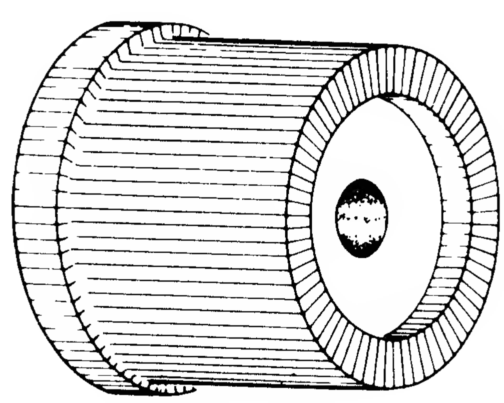


Fig. 2-8. A commutator for a brush-riding, repulsion-start, induction-run motor.

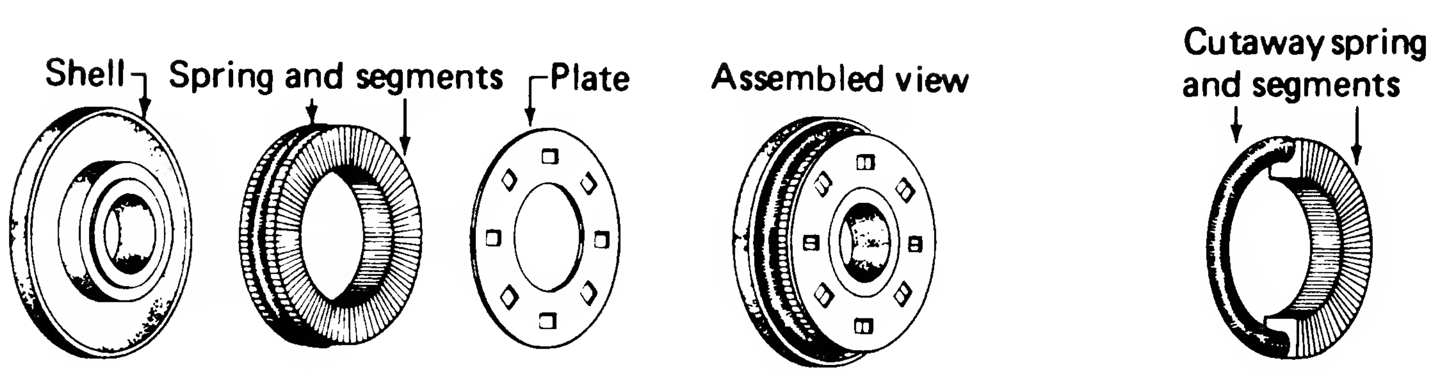
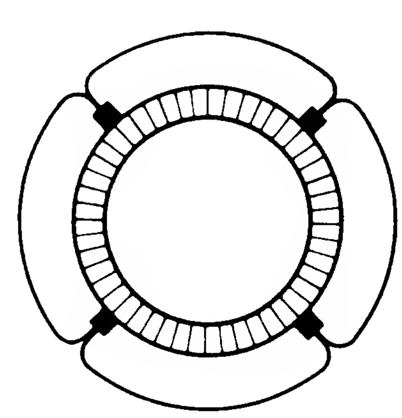


Fig. 2-9. The assembly of the short-circuiting device of a brush-riding, repulsion-start, induction-run motor.

Fig. 2-10. Four brushes are used on this four-pole motor. All brushes are connected together by a one-piece metal brush holder rigging and the pigtails on the brushes.



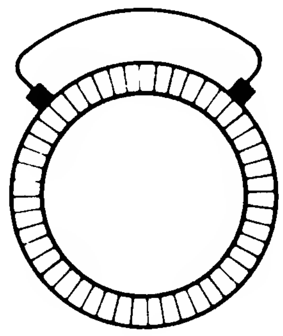


Fig. 2-11. Two brushes may be used for a four-pole motor if the armature is wave-wound or cross-connected.

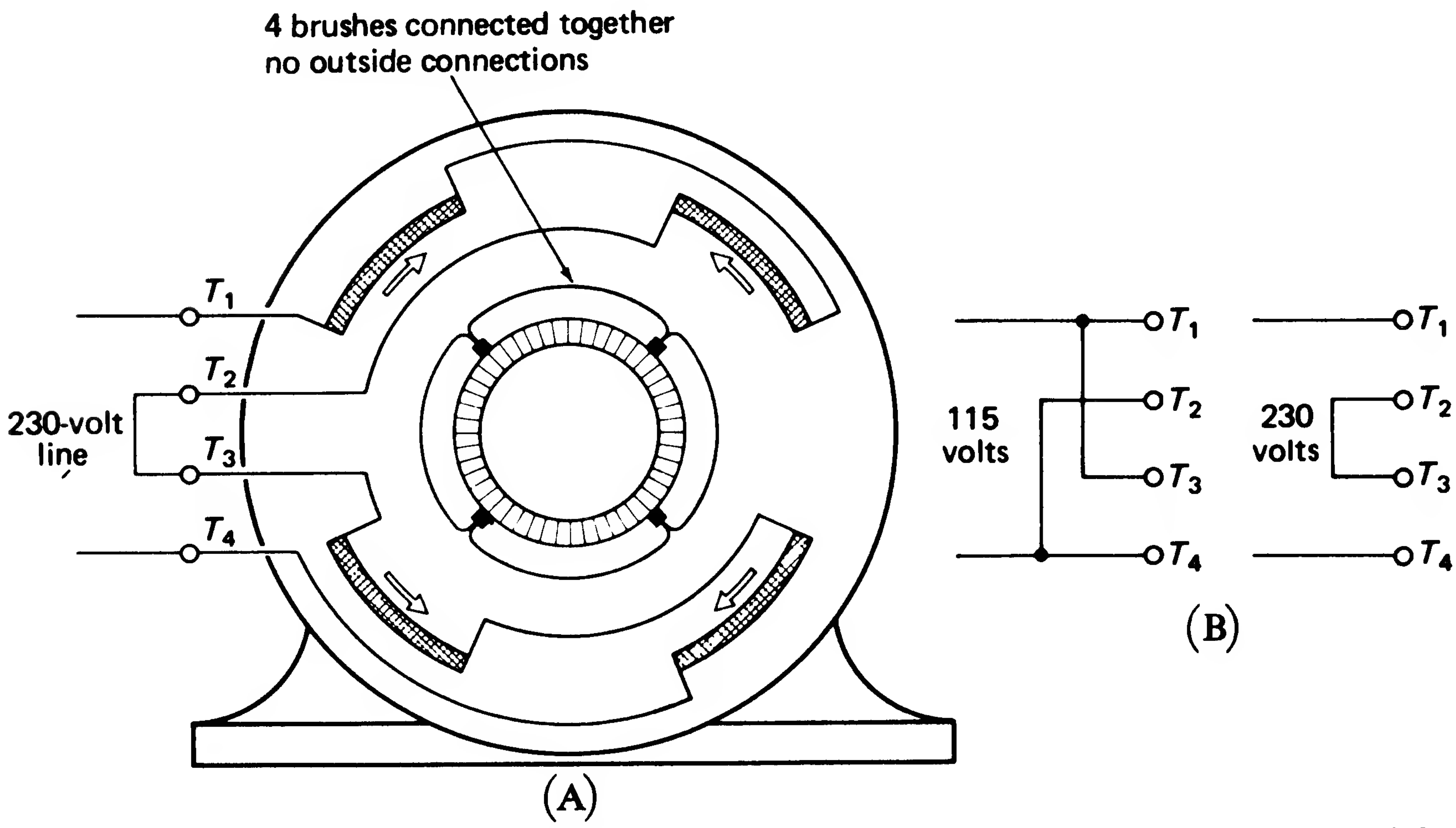


Fig. 2-12. A four-pole stator of a repulsion-start, induction-run motor, connected for 230 volts.

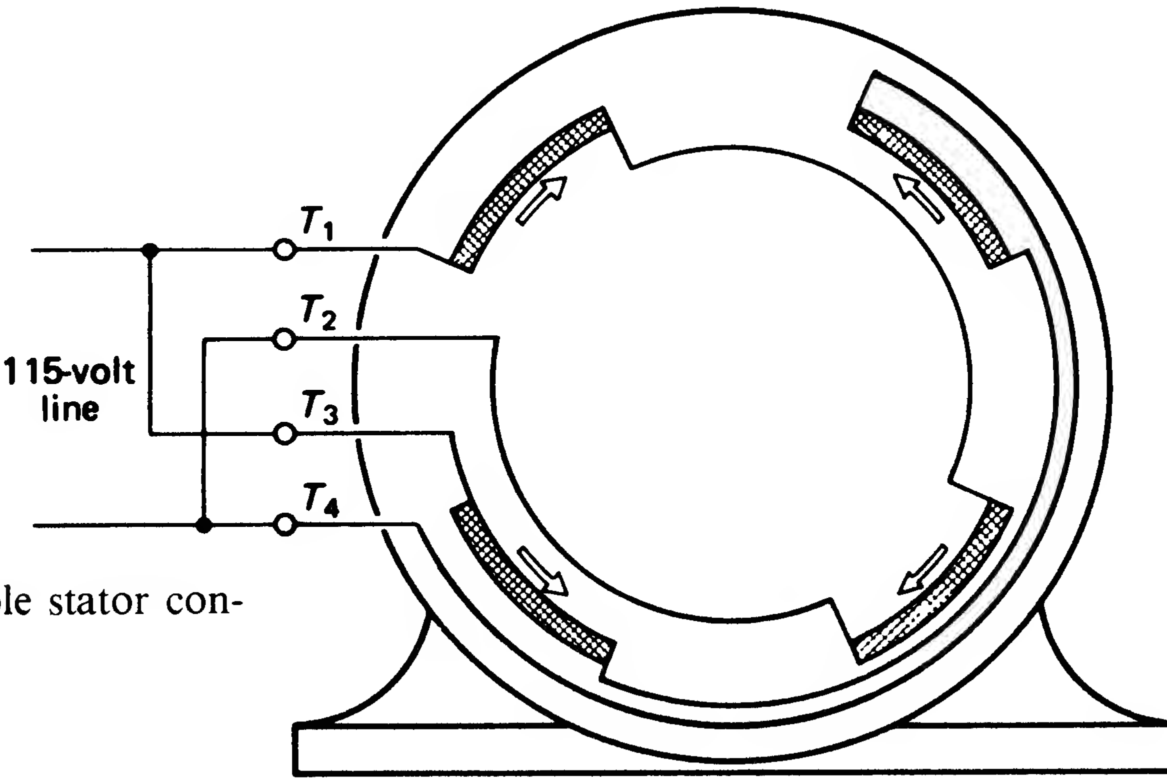


Fig. 2-13. A four-pole stator connected for 115 volts.

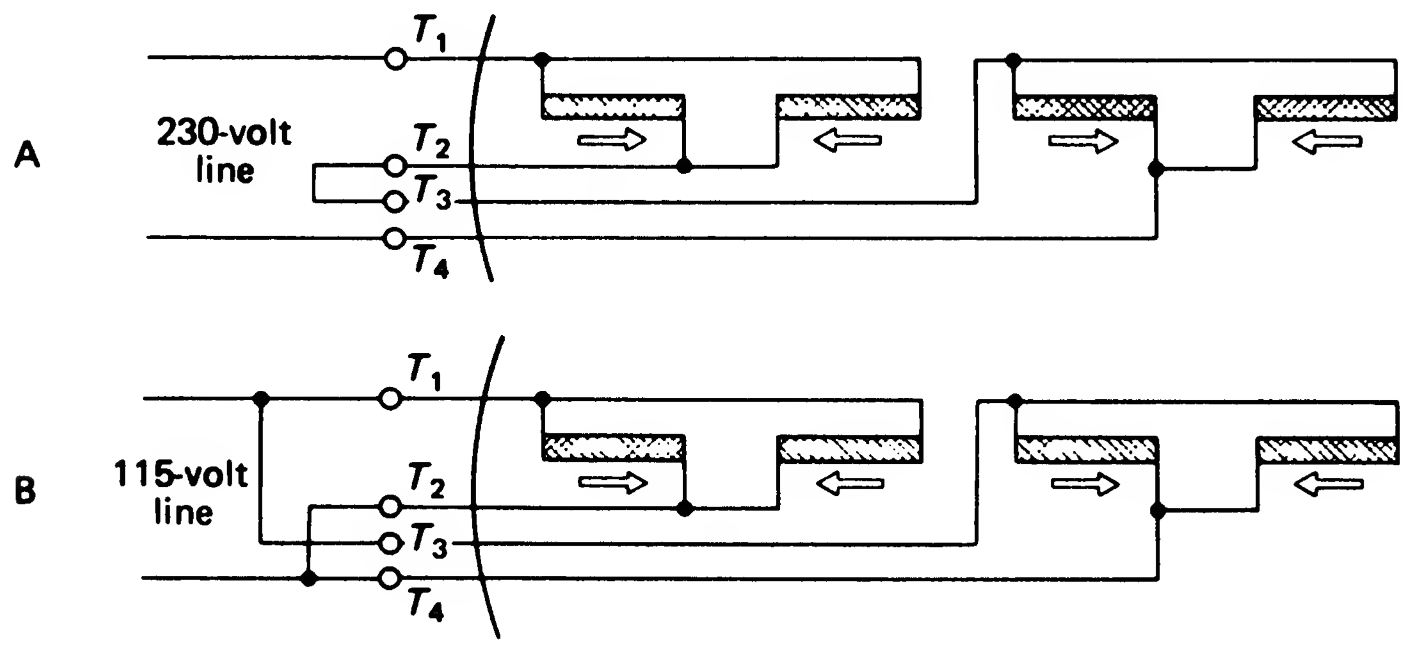


Fig. 2–14. A two-circuit connection for 230-volt operation (a). A four-circuit connection for 115-volt operation (b).

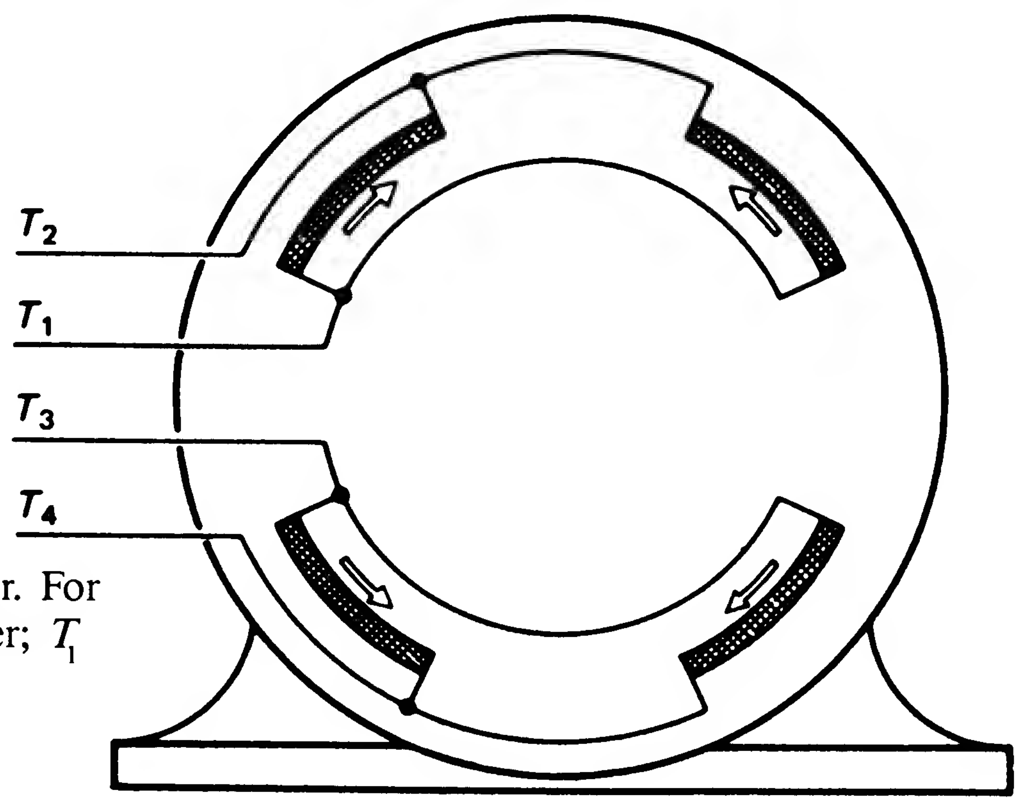


Fig. 2–15. A two-voltage motor. For 230 volts: connect T_2 and T_3 together; T_1 to line lead, and T_4 to line lead.

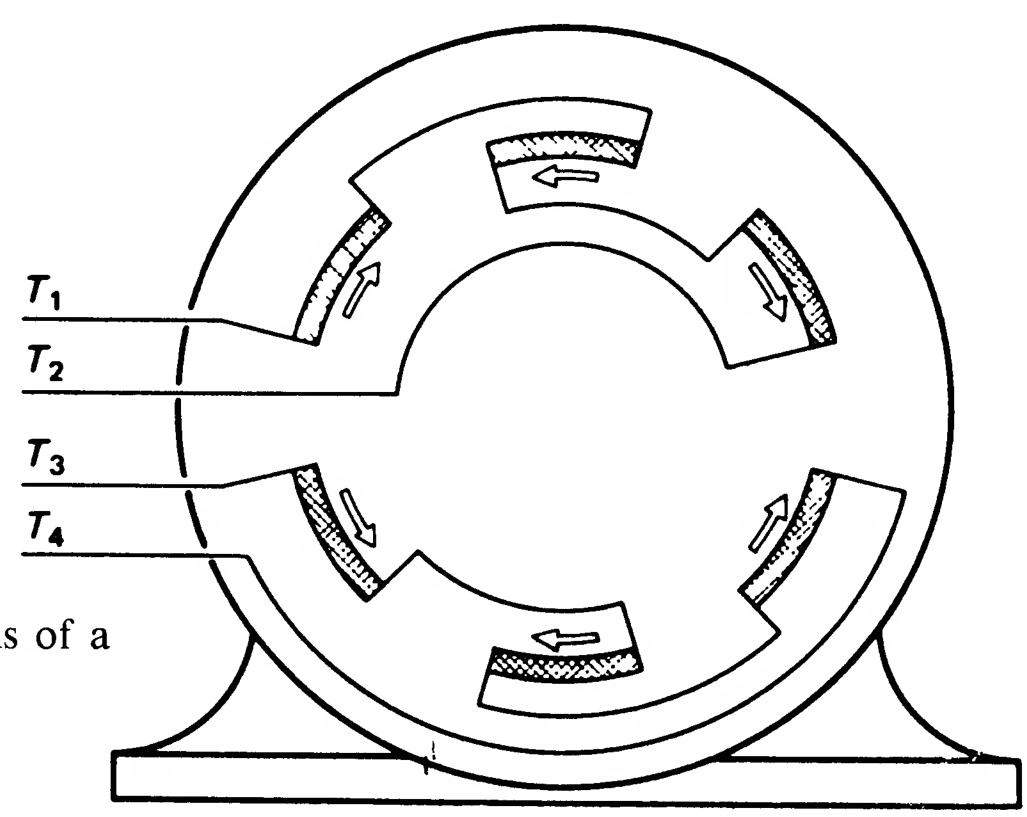


Fig. 2–16. Internal connections of a six-pole repulsion motor stator.

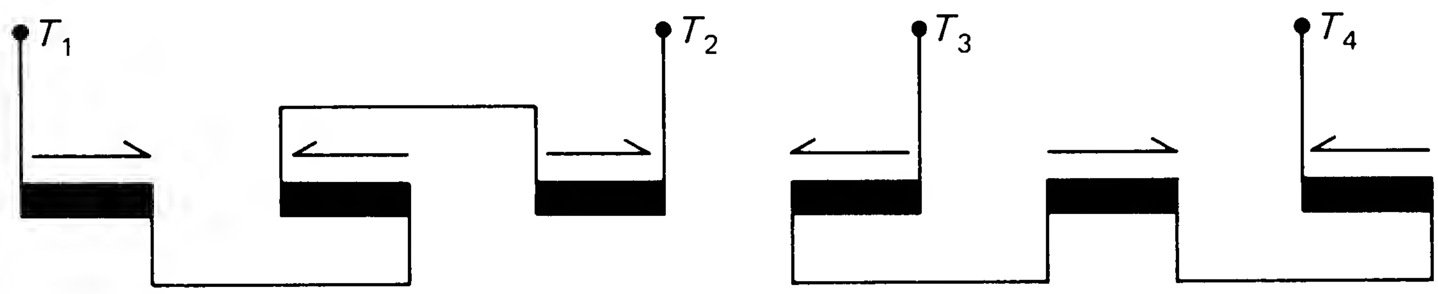


Fig. 2-17. A straight-line diagram of a six-pole stator with a short jumper or adjacent group connection.

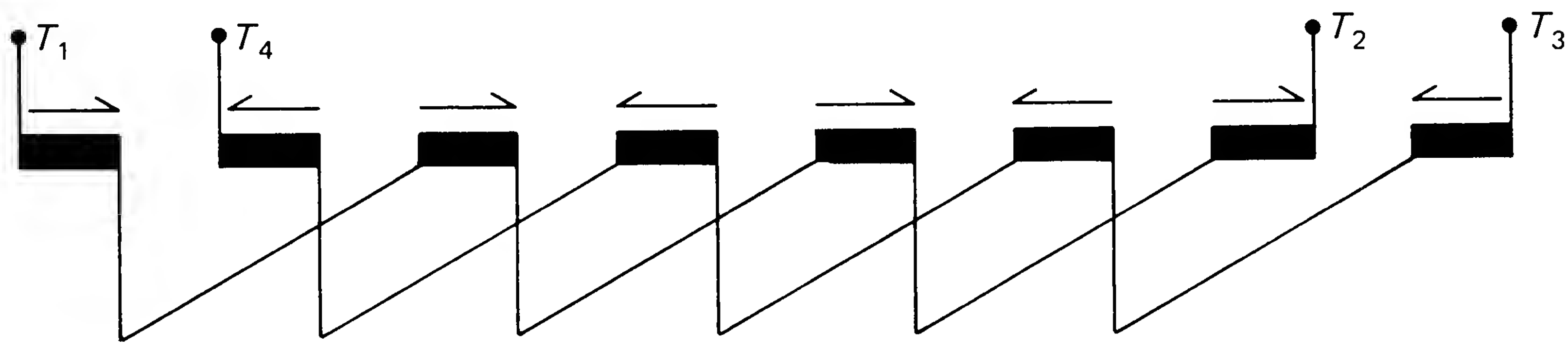


Fig. 2-18. A straight-line diagram of an eight-pole stator with long jumper connections.

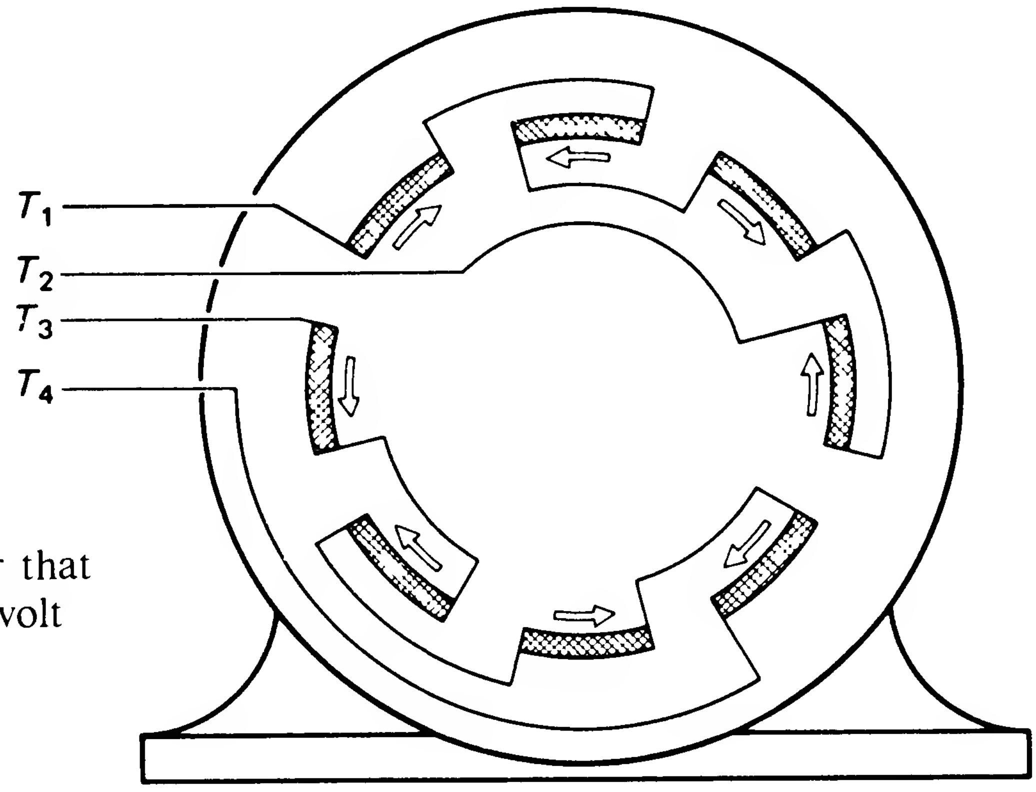


Fig. 2-19. An eight-pole stator that can be connected for 115- or 230-volt operation.

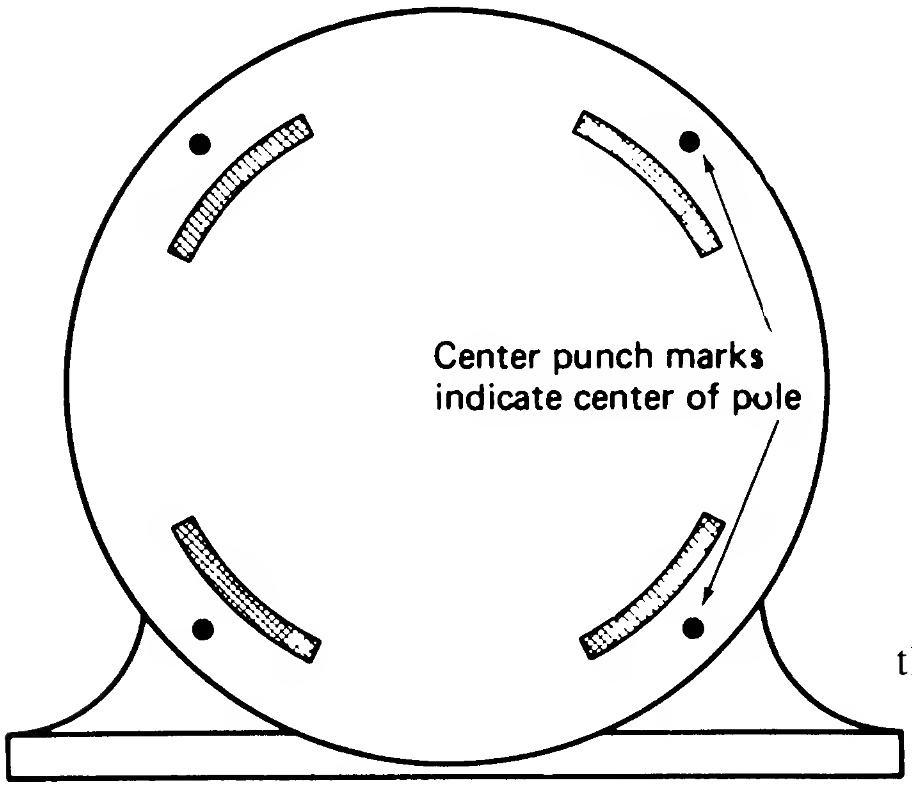


Fig. 2-20. Recording the position of the poles in a repulsion motor.

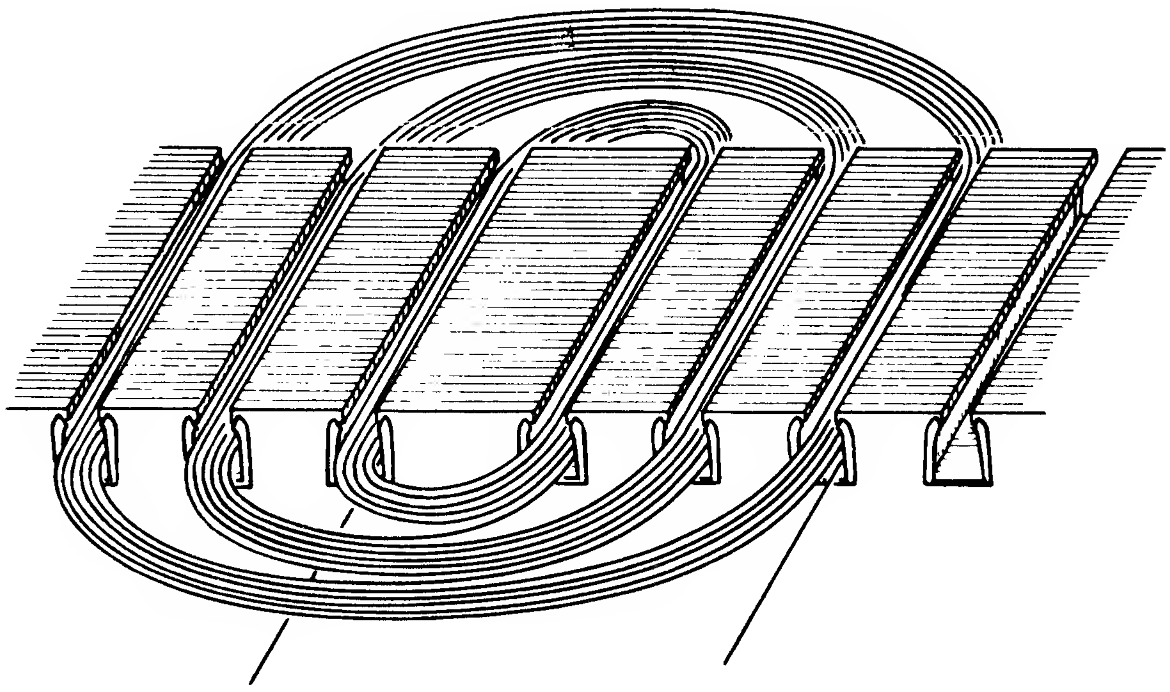


Fig. 2–21. The core section at the center of the pole. It is wider than other sections.

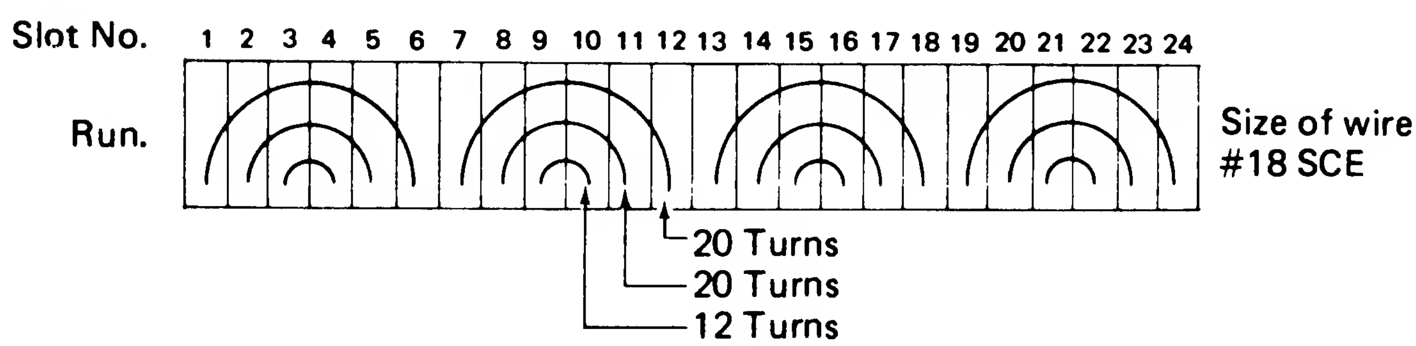


Fig. 2–22. The method of recording data for a 24-slot, repulsion-start, induction-run motor.

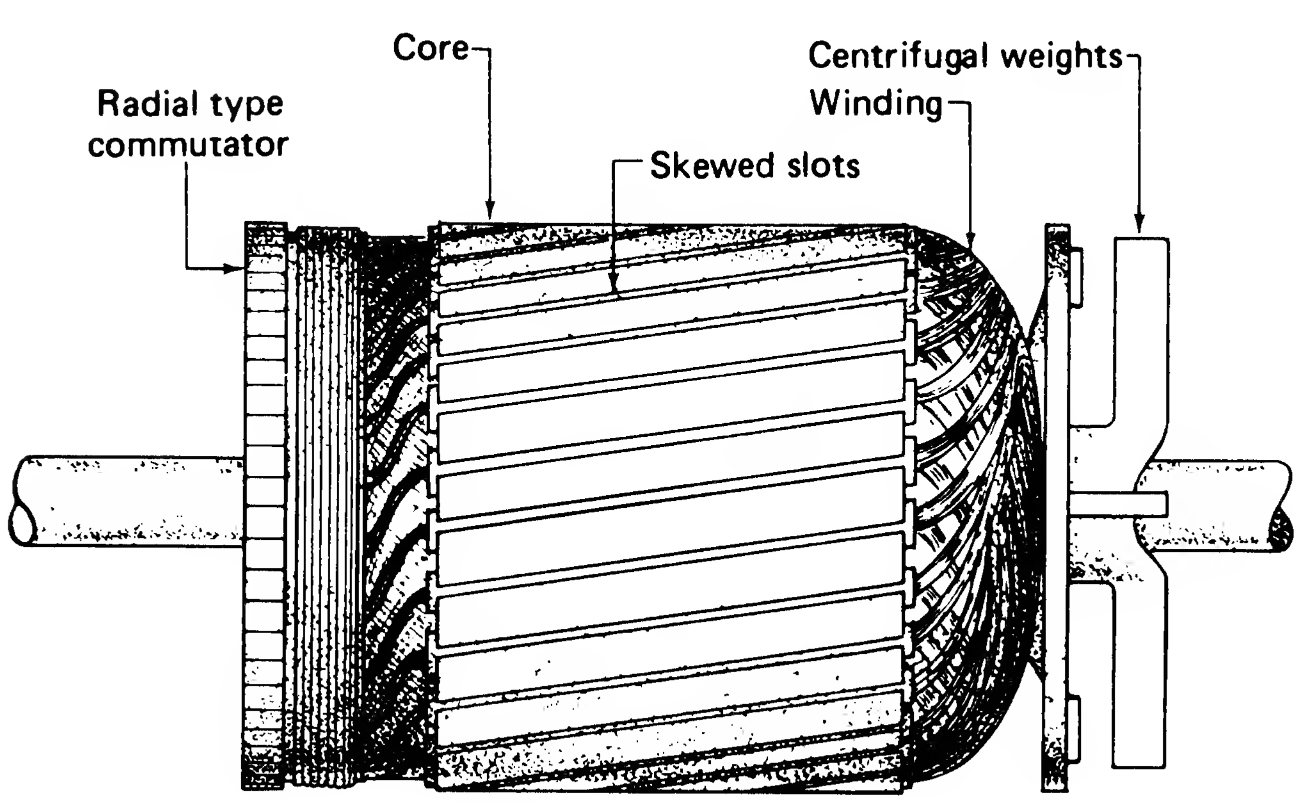


Fig. 2–23. The armature of a repulsion-start, induction-run motor.

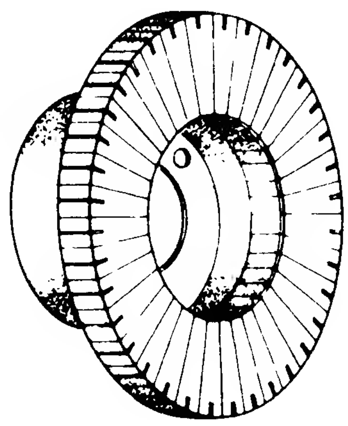


Fig. 2-24. A radial commutator that is pressed on the armature shaft.

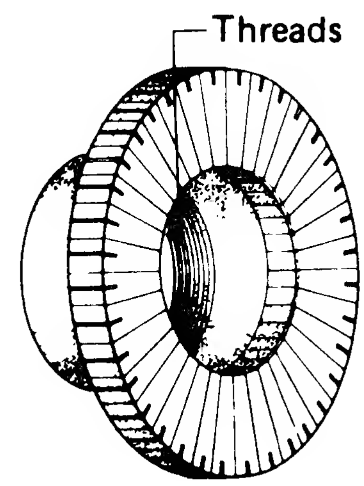


Fig. 2-25. A radial commutator that screws onto the armature shaft.

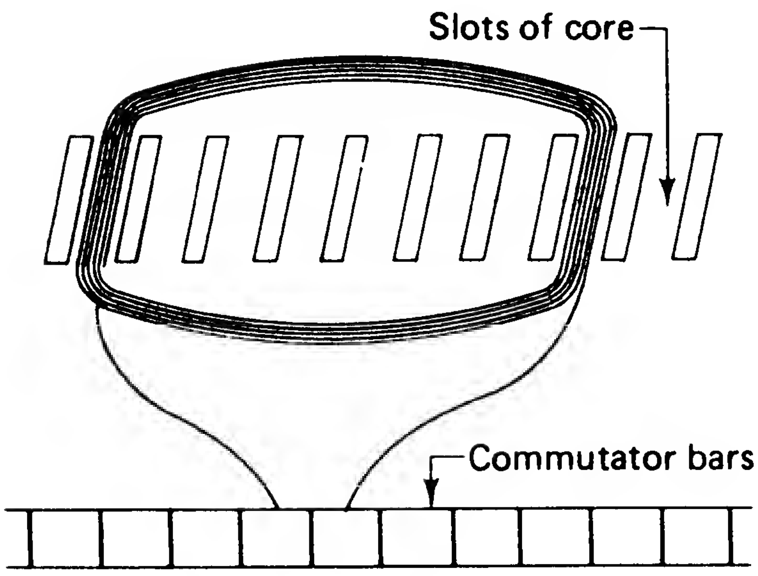


Fig. 2-26. A lap winding with one coil per slot.

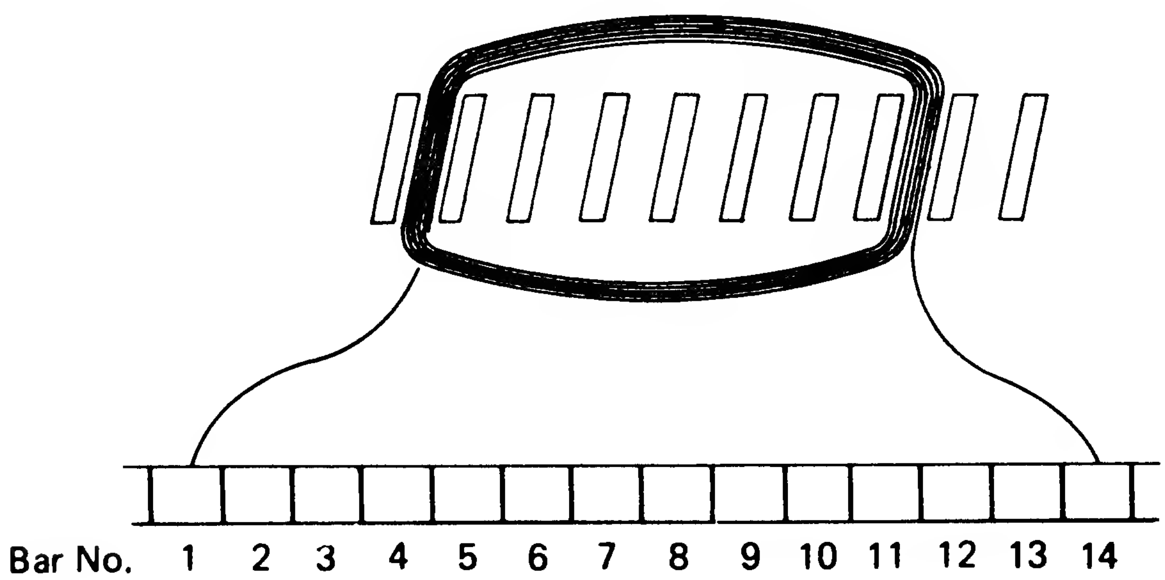


Fig. 2-27. A wave winding with one coil per slot.

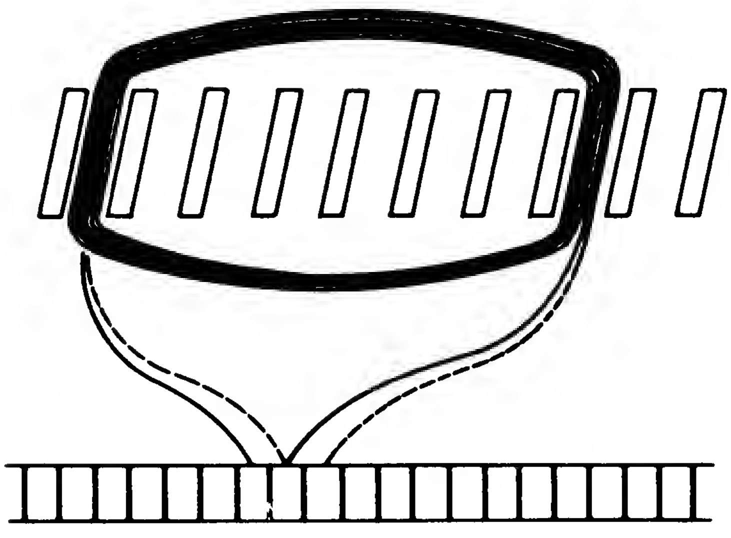
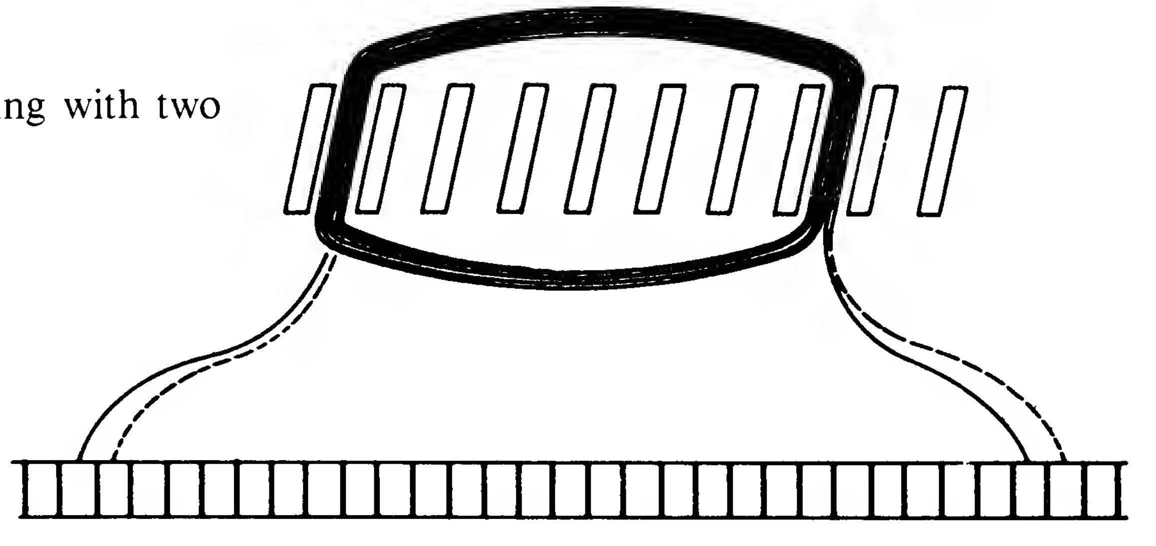


Fig. 2–28. A lap winding with two coils per slot.

Fig. 2–29. A wave winding with two coils per slot.



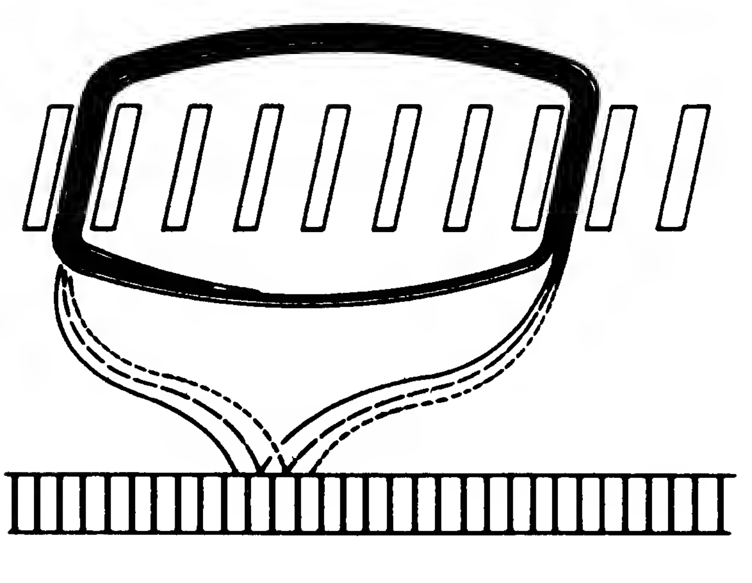
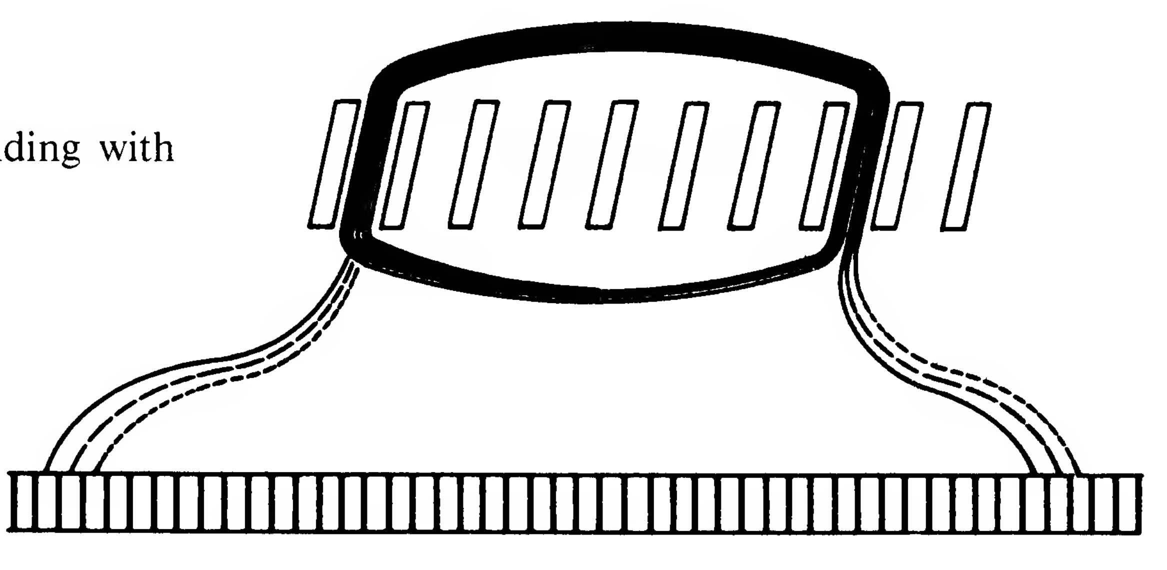


Fig. 2–30. A lap winding with three coils per slot.

Fig. 2–31. A wave winding with three coils per slot.



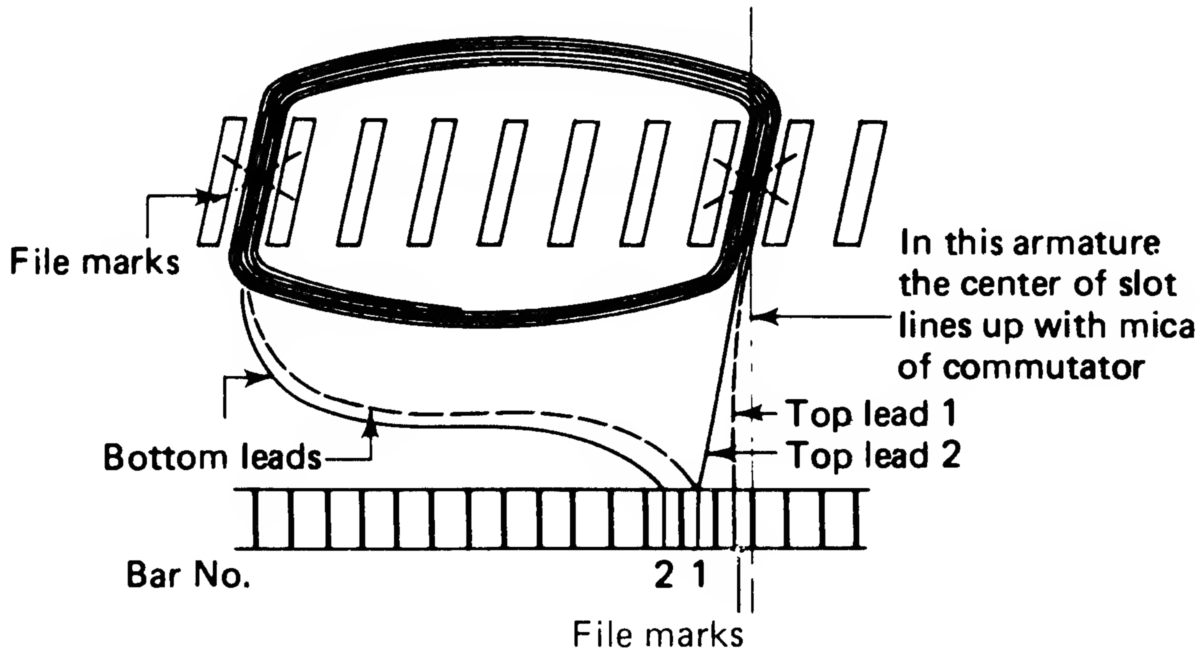


Fig. 2-32. Step 1. Record the data for a two-coil per-slot repulsion armature.

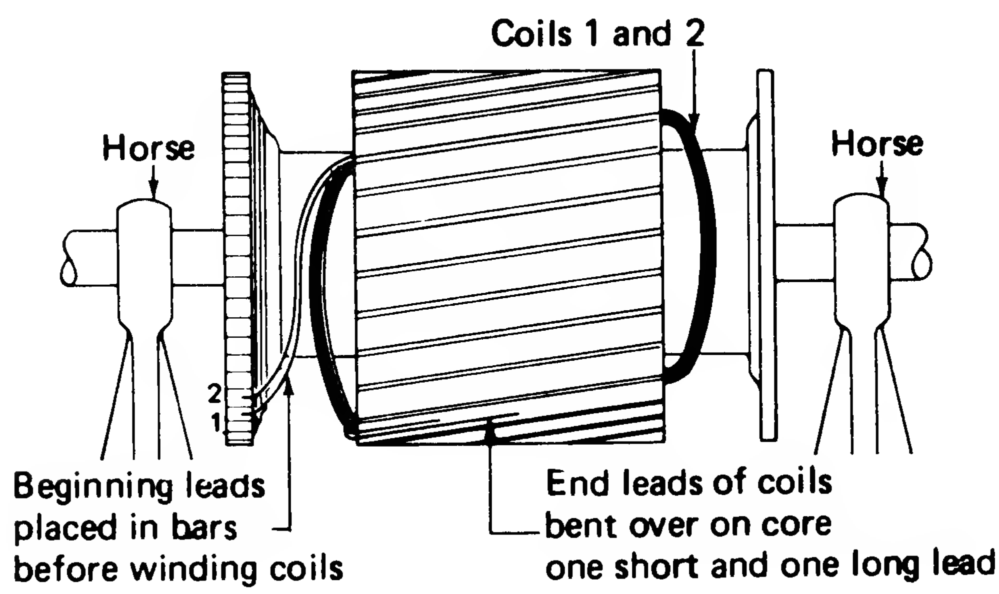


Fig. 2-33a. Step 2. Place beginning leads in adjoining commutator bars according to data and wind the proper number of turns, using two wires in hand. Cut the wires at the last turn and bend them over the core.

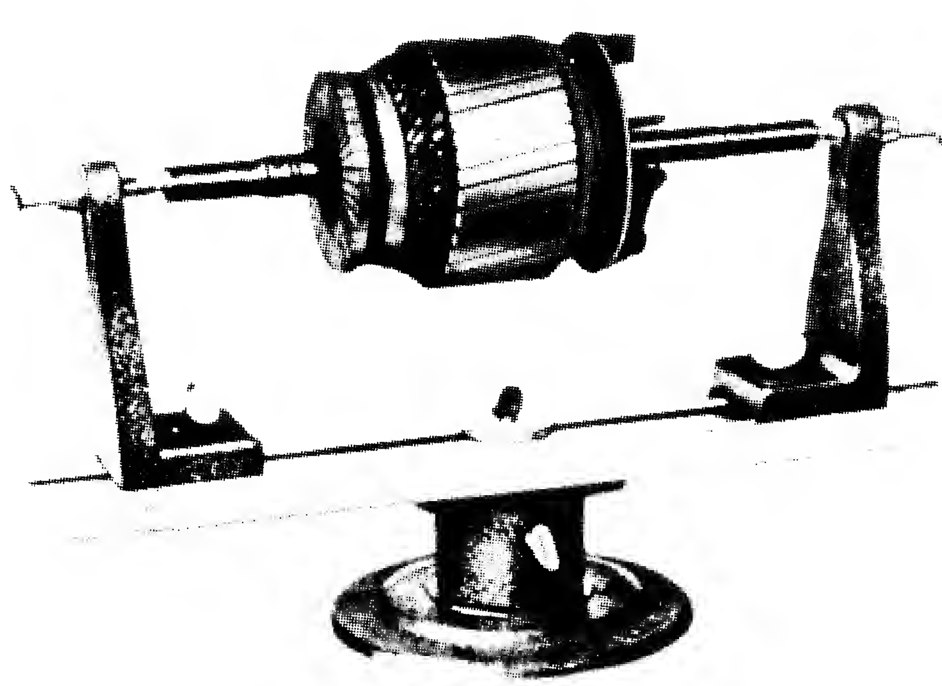


Fig. 2-33b. Armature holder. *(Crown Industrial Products)*

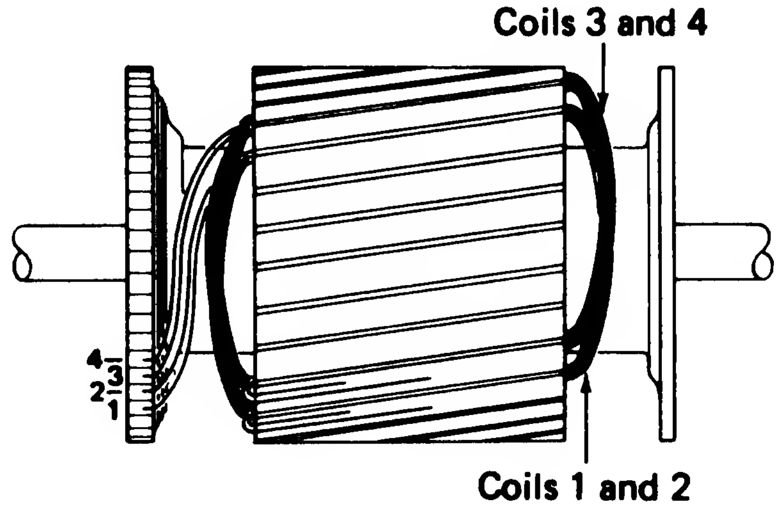


Fig. 2-34. Step 3. Place the beginnings of coils *3* and *4* in bars *3* and *4* and start winding the coils, beginning one slot away from the first coils and using the same pitch as before.

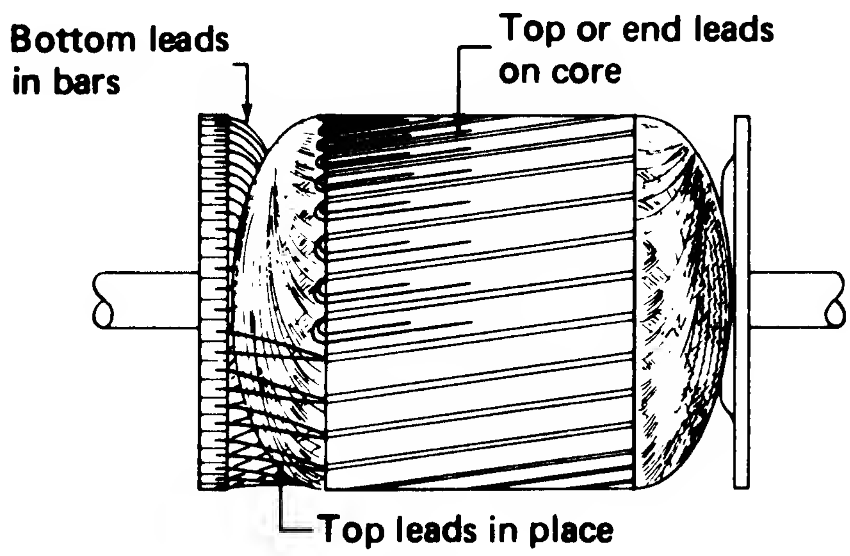
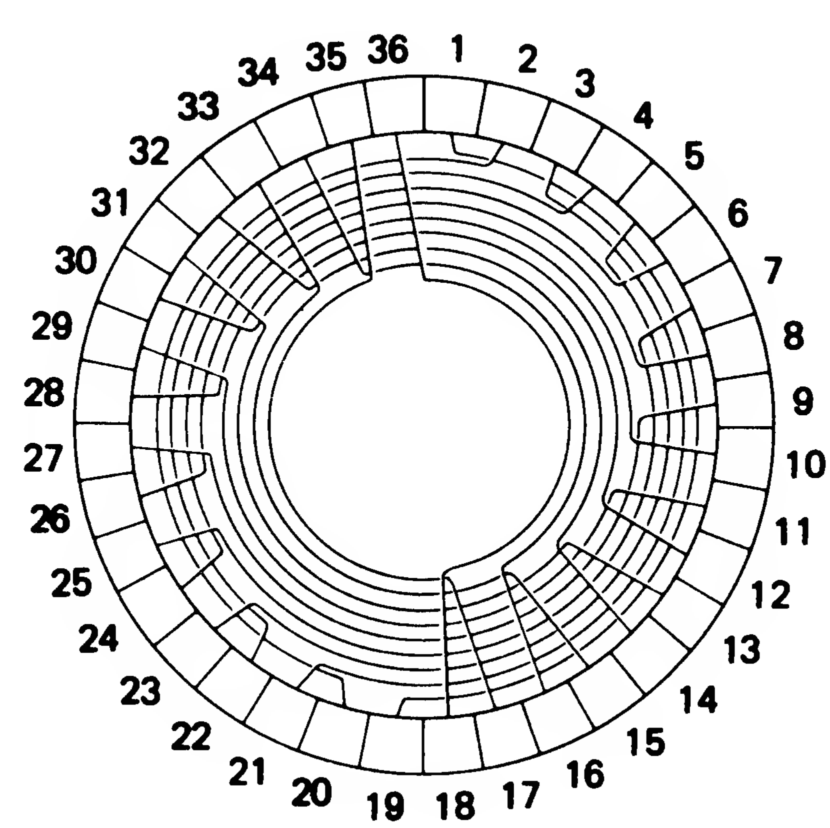


Fig. 2-35. Step 4. Place the top leads in the commutator bars after the armature is completely wound. For a lap winding, the top leads are placed in bars adjacent to the bottom leads of the same coil.

Fig. 2-36. Cross connections of commutator bars for a four-pole motor having 36 bars, pitch 1 and 19.



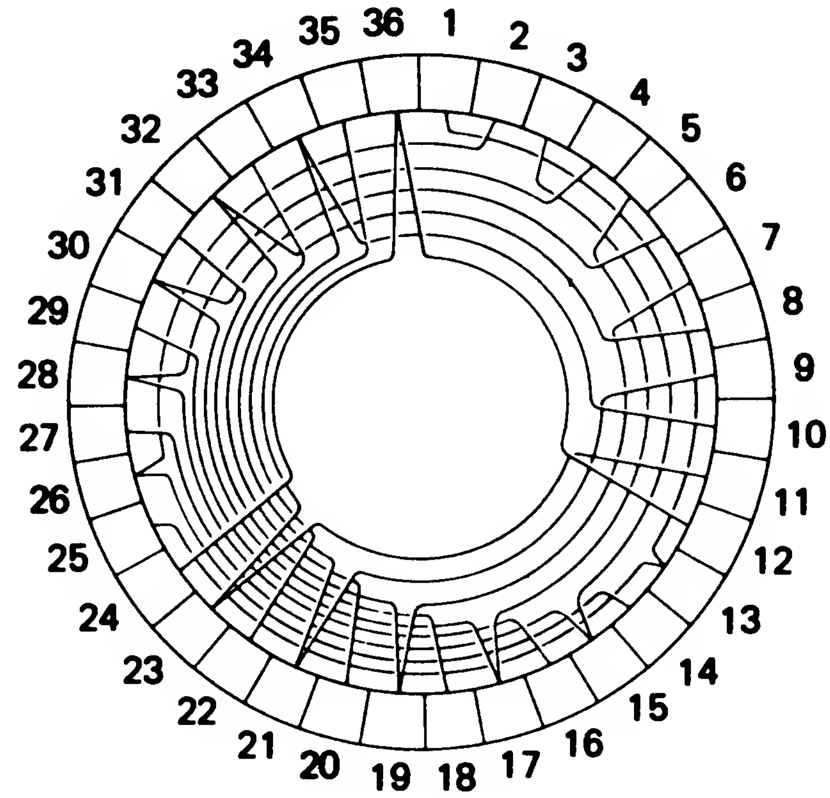


Fig. 2-37. Cross connections of commutator bars for a six-pole motor having 36 bars, pitch 1 and 13.

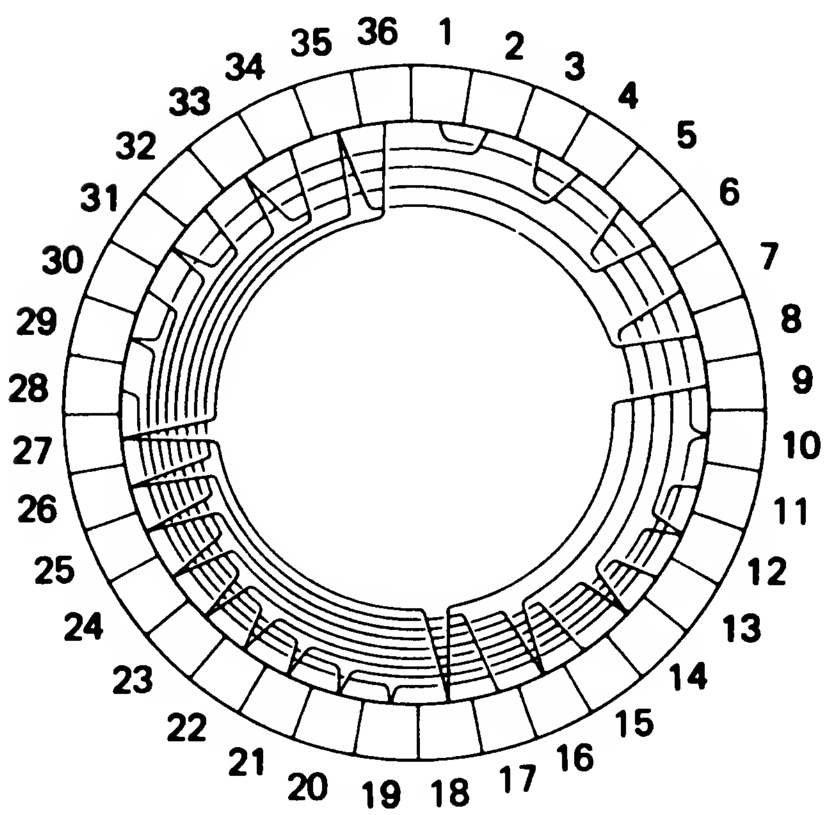
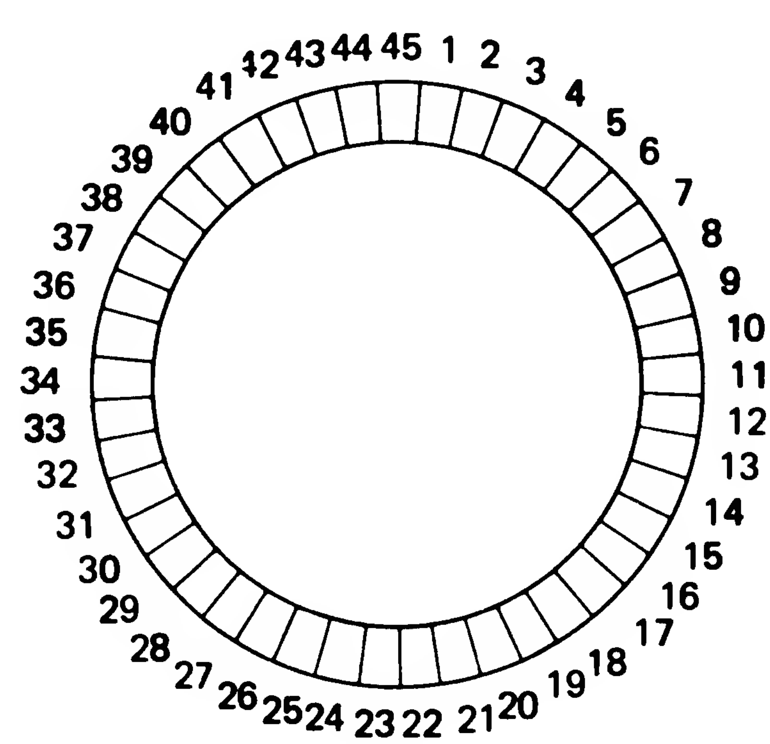


Fig. 2-38. Cross connections of commutator bars for an eight-pole motor having 36 bars, pitch 1 and 10.

Fig. 2-39. A four-pole, wave-wound armature must have an odd number of bars in the commutator. If there is an even number of bars, two must be shorted.



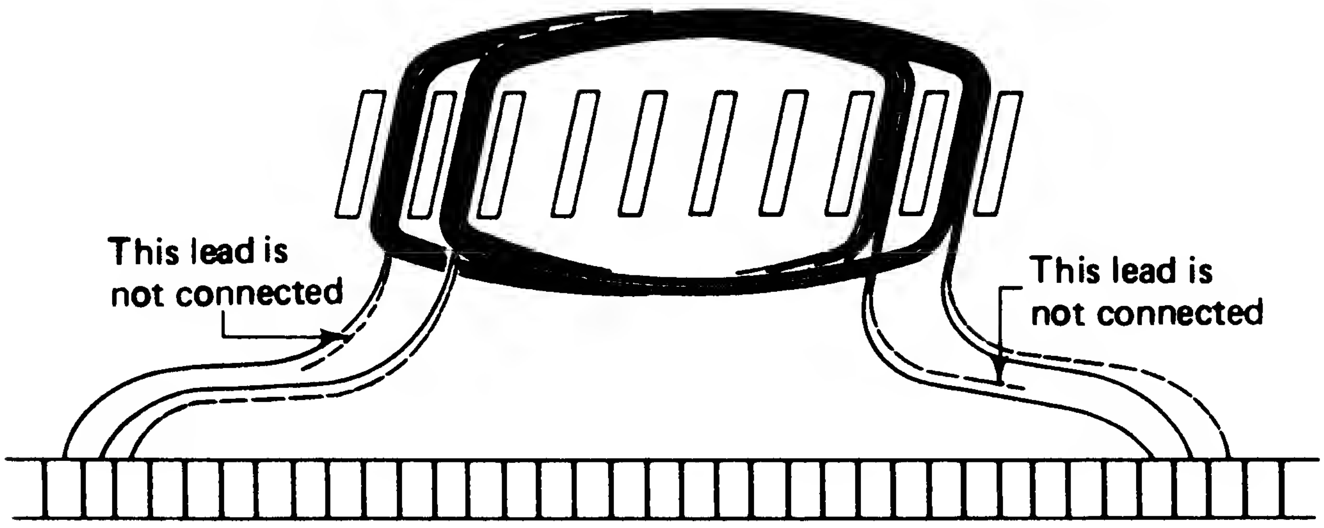


Fig. 2–40. A wave connection showing dead coil. This coil must remain unconnected when there are more coils than bars.

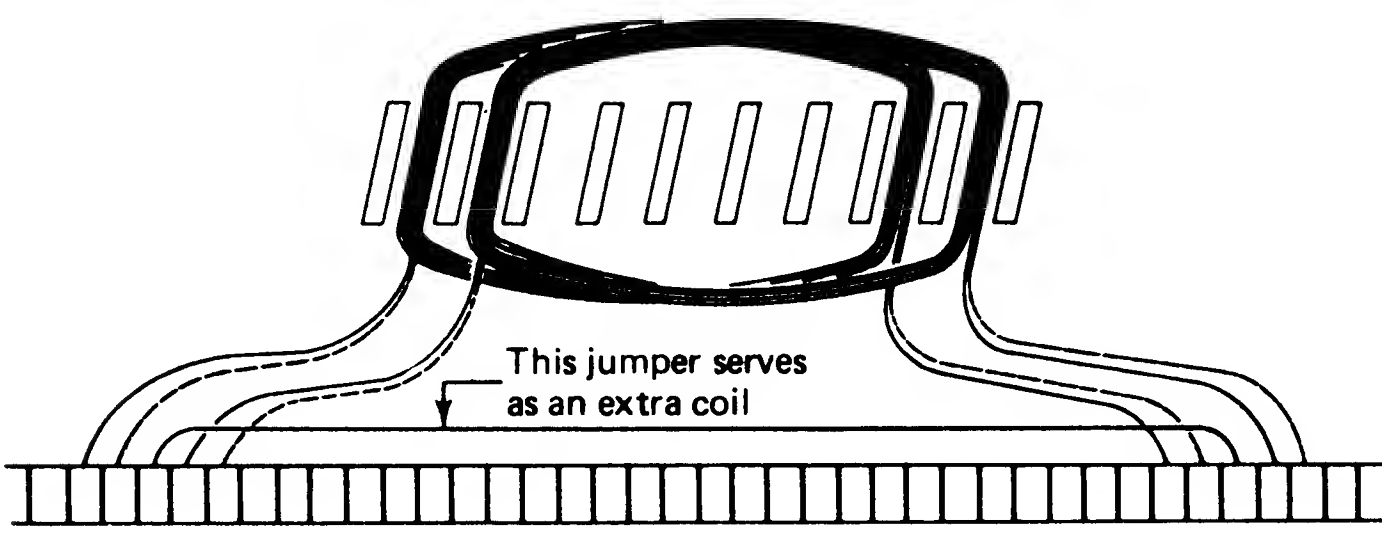


Fig. 2–41. The method of placing a jumper between two bars to take the place of a coil. This is used when there is an even number of coils and one bar more than the number of coils.

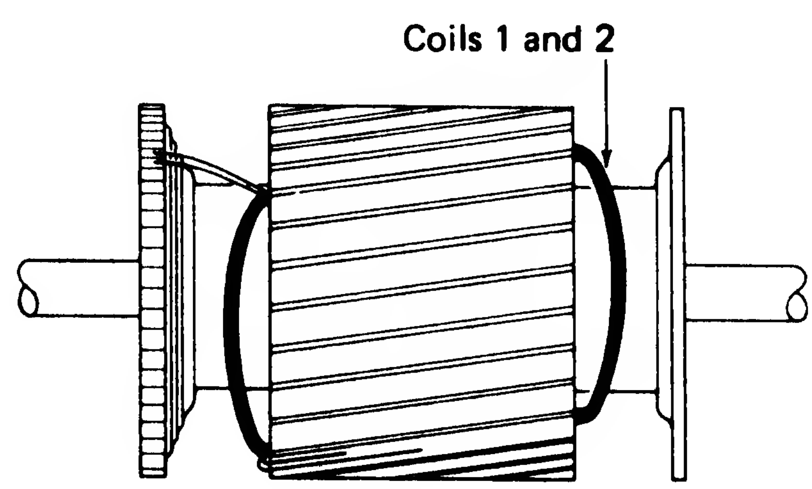


Fig. 2–42. The first two coils of a wave-wound armature in place. Note that this armature is wound exactly as a lap armature, except that the beginning leads are placed away from the center of the coil.

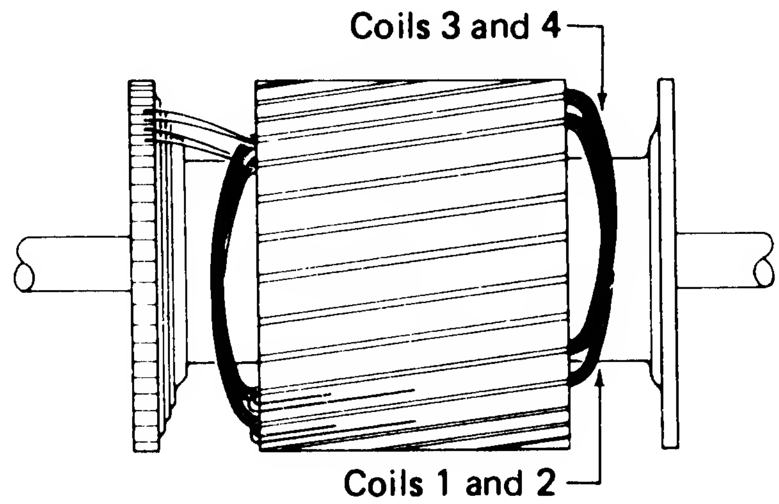


Fig. 2-43. The next two coils placed in the slots exactly as the first two coils, except that they are started in the next slot. The end leads are cut off and left on the core.

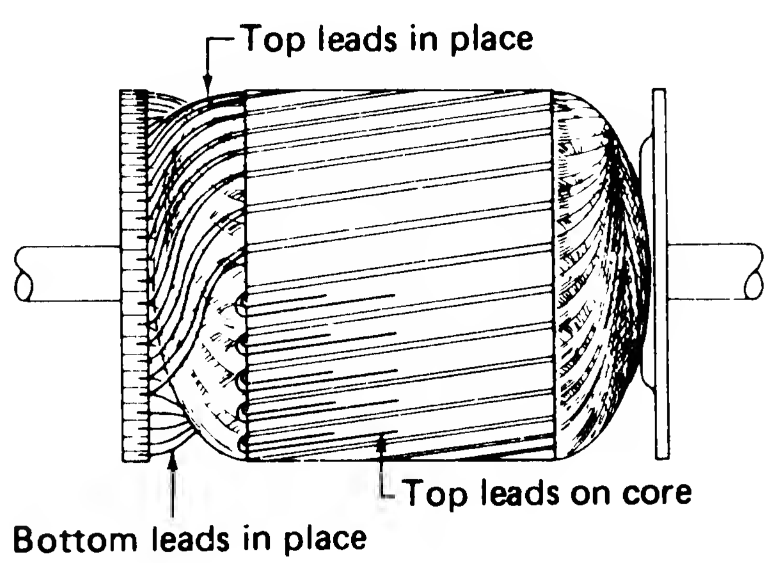


Fig. 2-44. How the top leads are placed in bars for a wave winding.

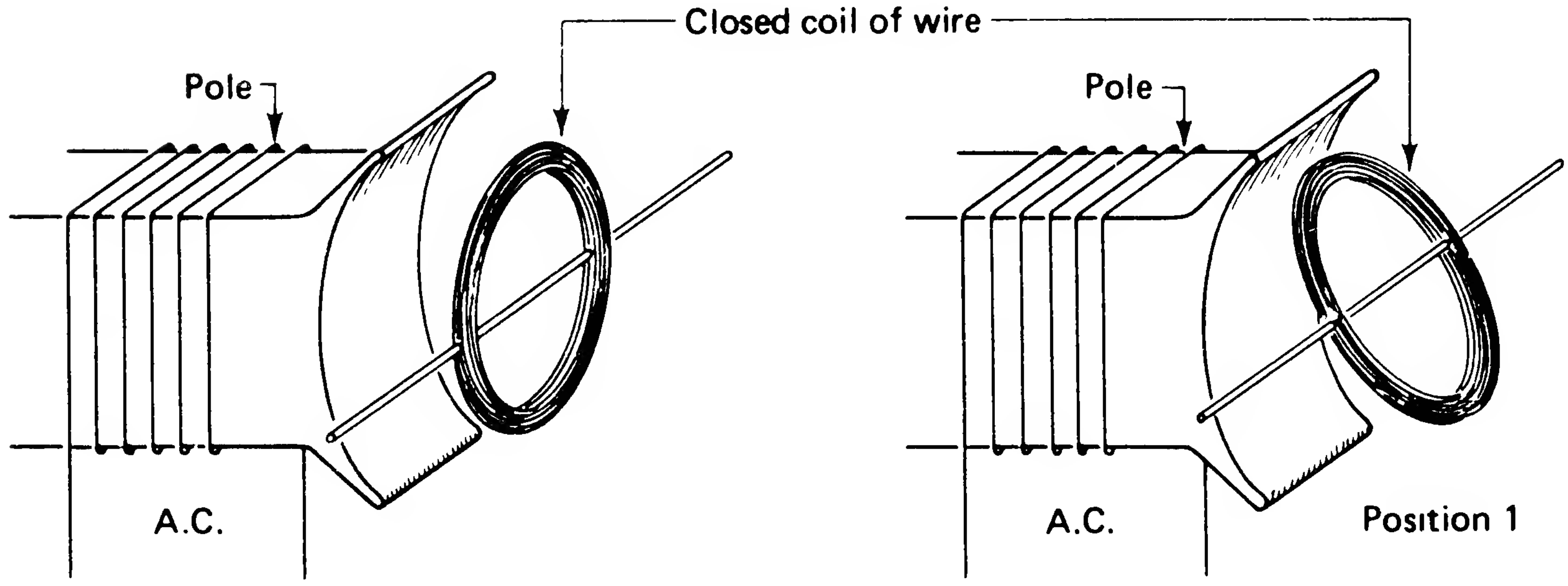


Fig. 2-45. If the coil is in a vertical plane, it will not move. If the coil is tilted off the vertical, it will tend to move.

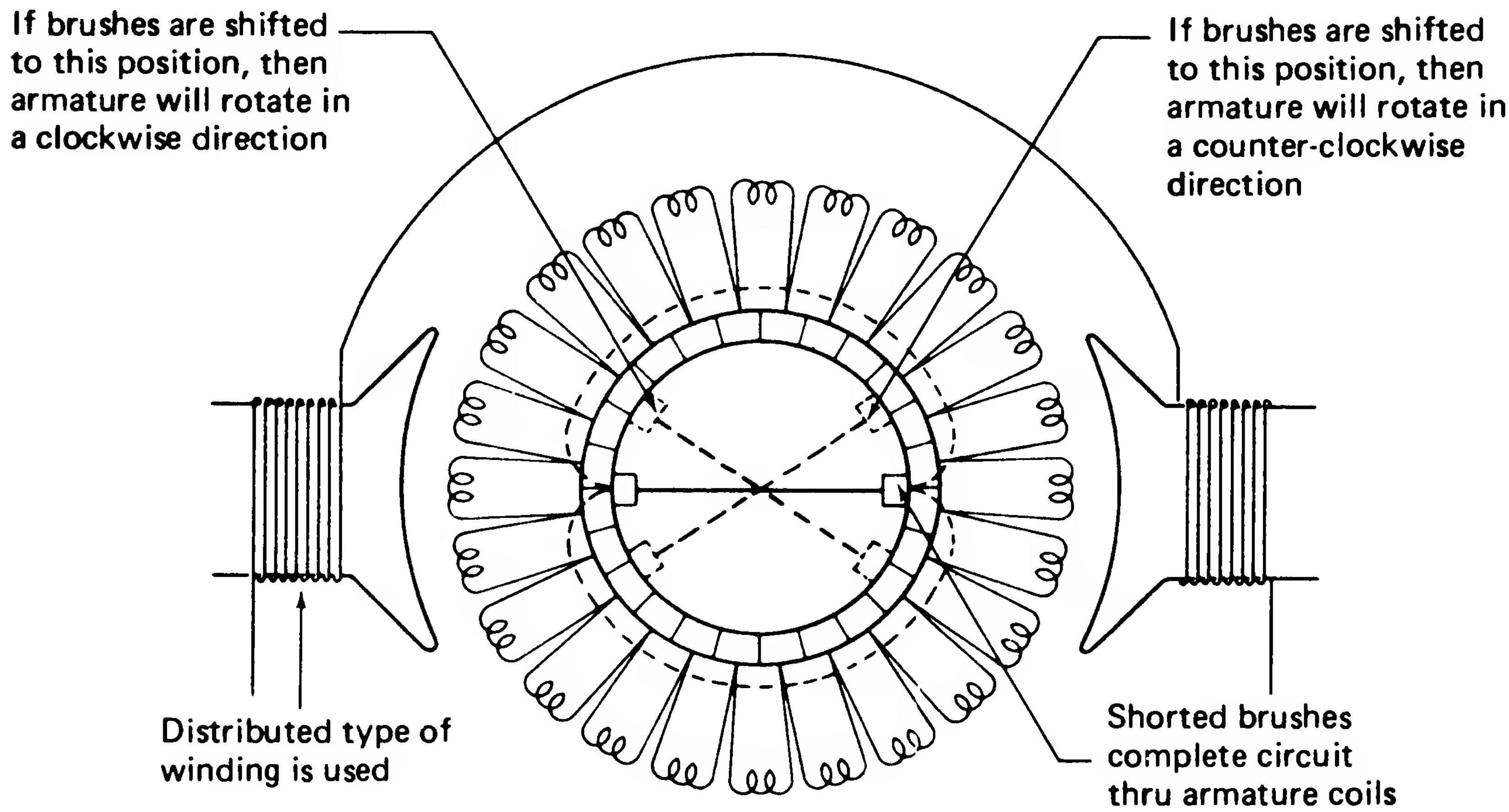


Fig. 2-46. Two closed circuits in an armature similar to two coils. No motion takes place if brushes are in a vertical or horizontal postion.

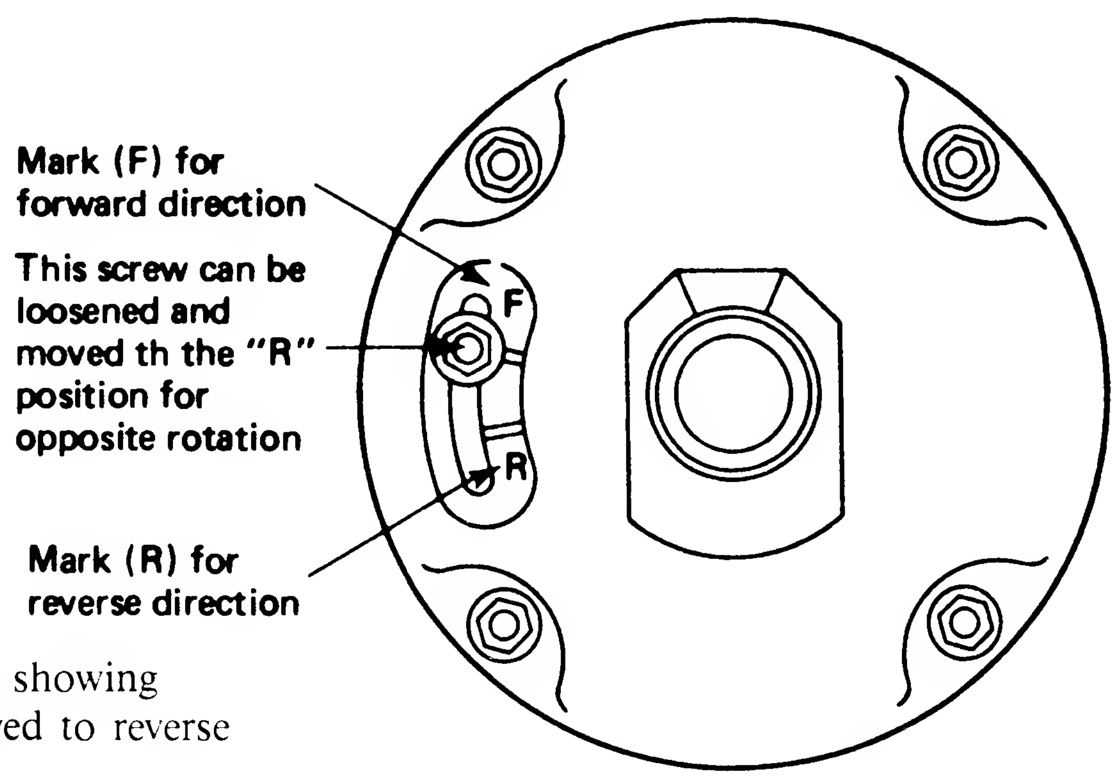


Fig. 2-47. An end plate showing how the brush holder is moved to reverse the motor.

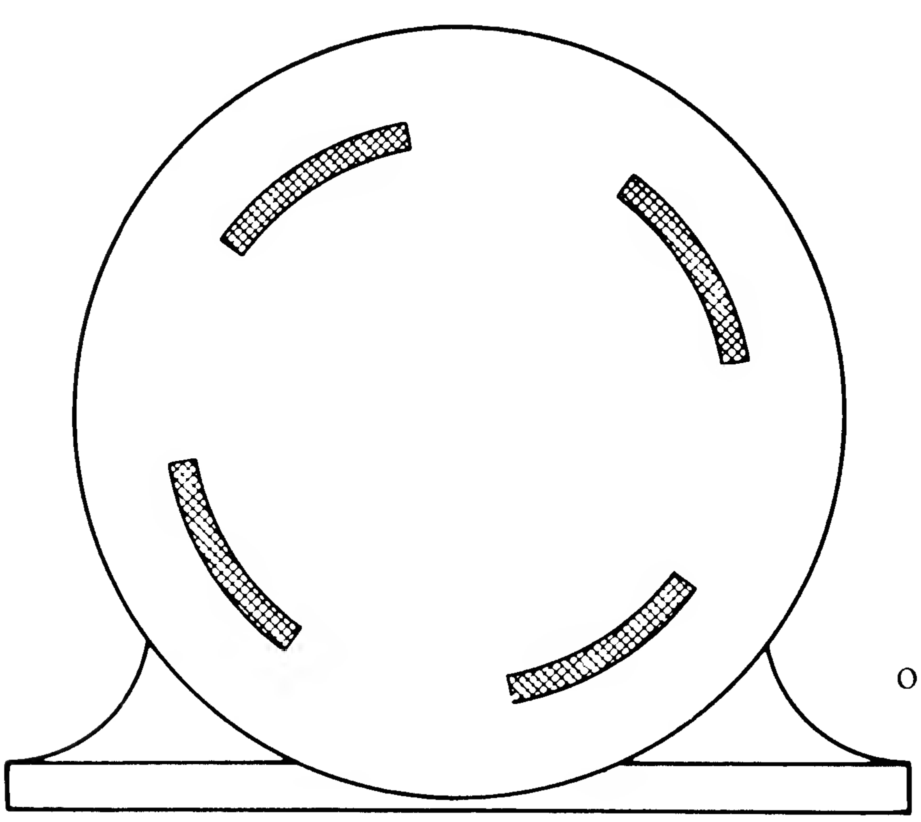


Fig. 2-48. A frame with field poles off center.

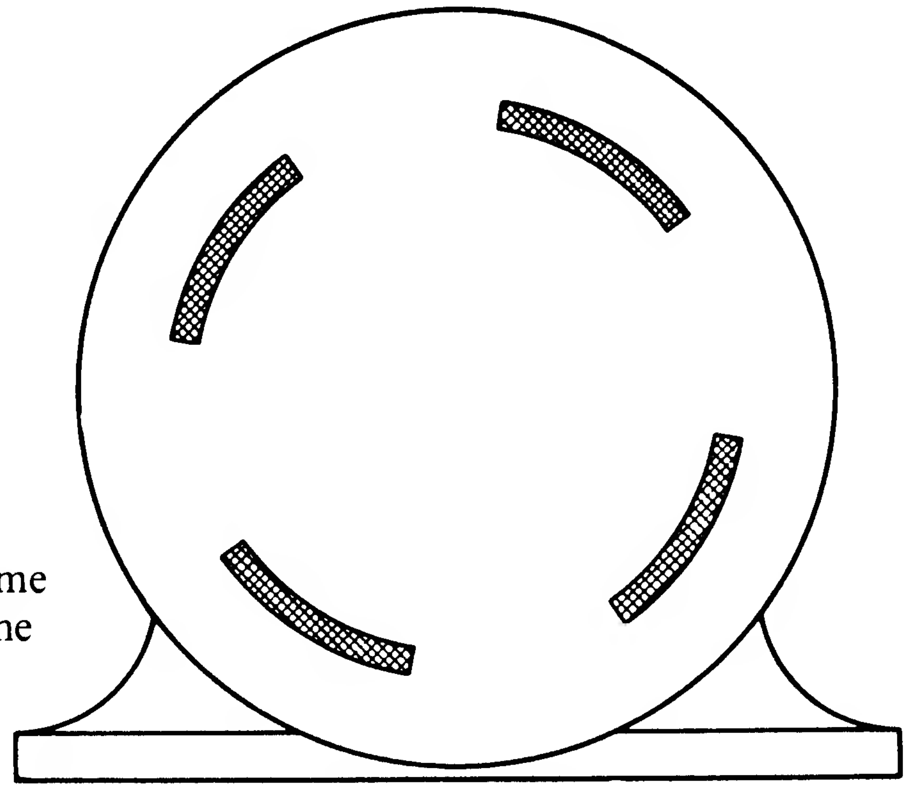


Fig. 2-49. The position of the frame in **Fig. 2-48** reversed. This will cause the motor to run in the opposite direction.

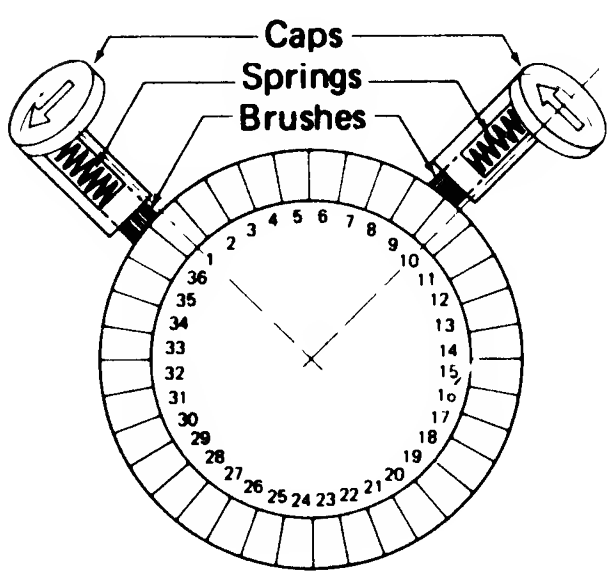


Fig. 2-50. A cartridge type of brush holder with both brushes in position for counterclockwise rotation.

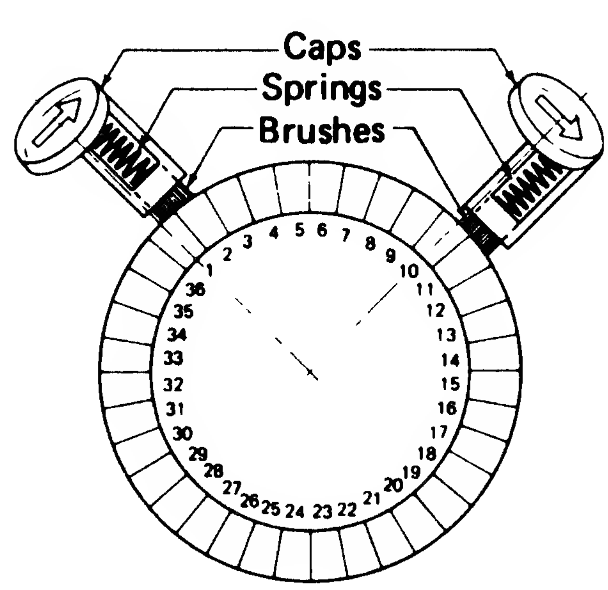


Fig. 2-51. A cartridge type of brush holder with both brushes in position for clockwise rotation.

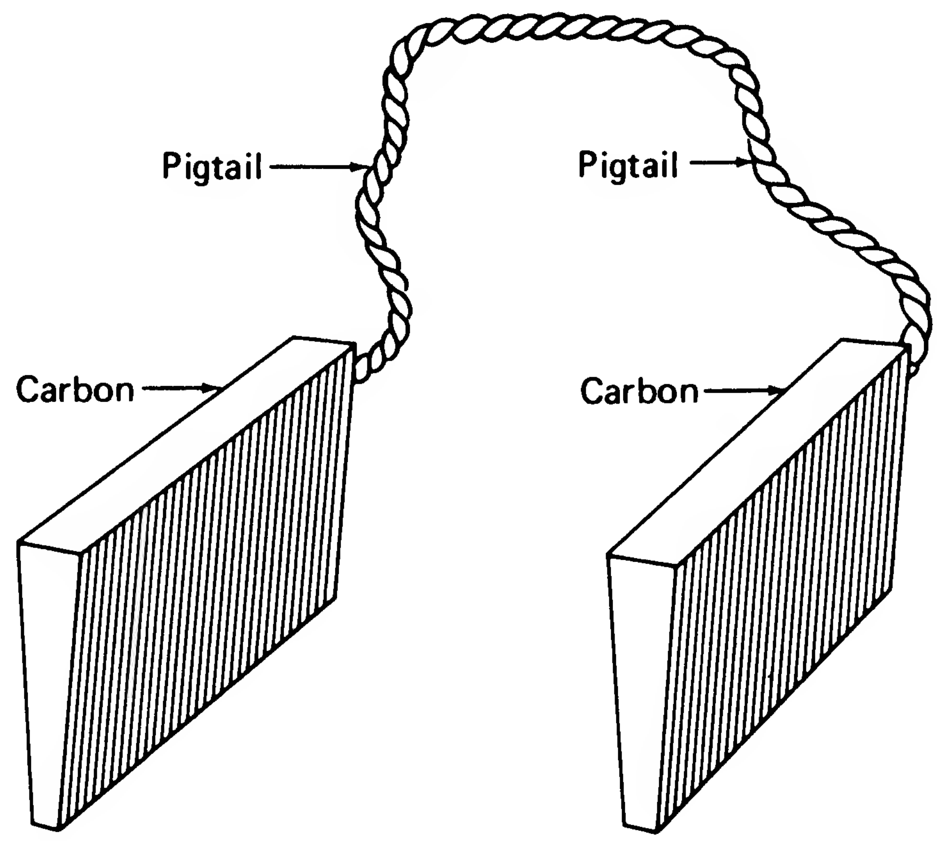


Fig. 2-52. Pair of wedge shaped brushes for a vertical commutator.

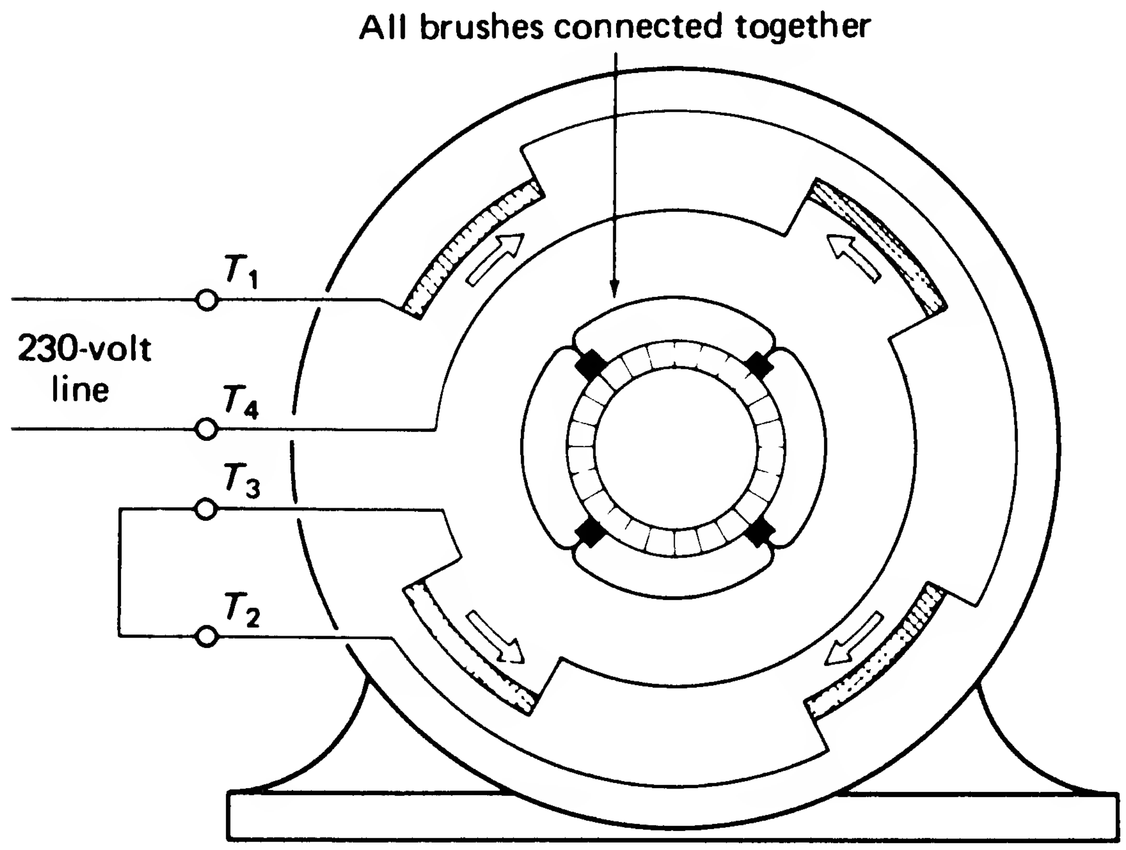


Fig. 2-53. A four-pole repulsion motor. Note that the motor can be connected for two voltages. Four brushes are used. If the armature is wave-wound or cross-connected, two adjacent brushes may be used.

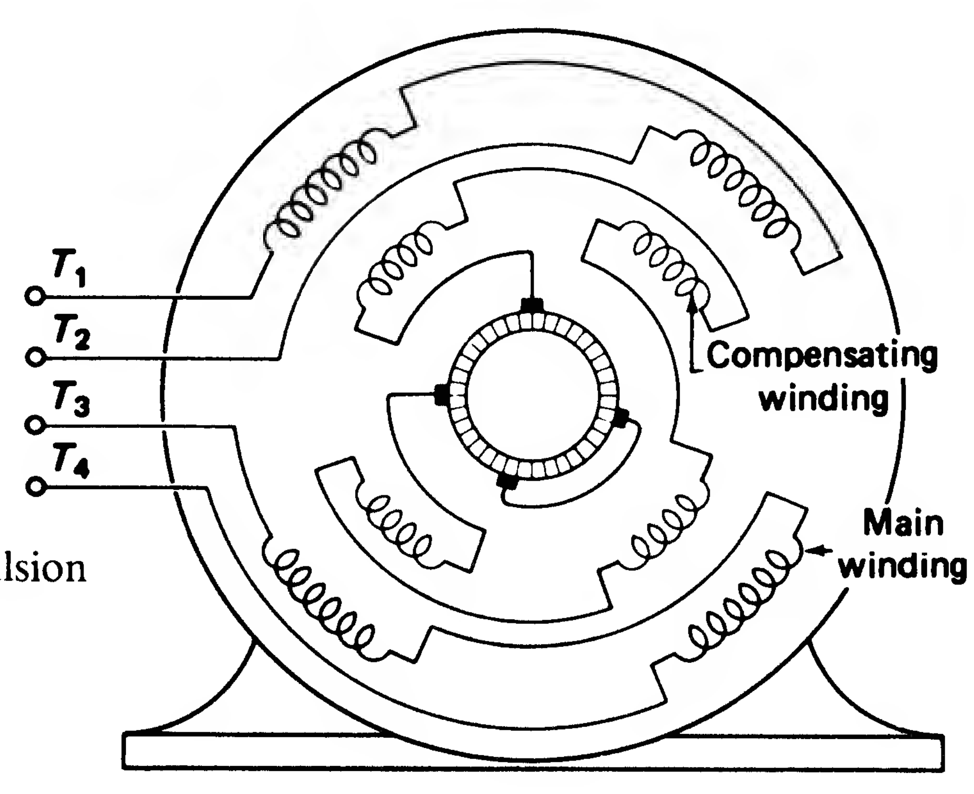


Fig. 2-54. A compensated repulsion motor.

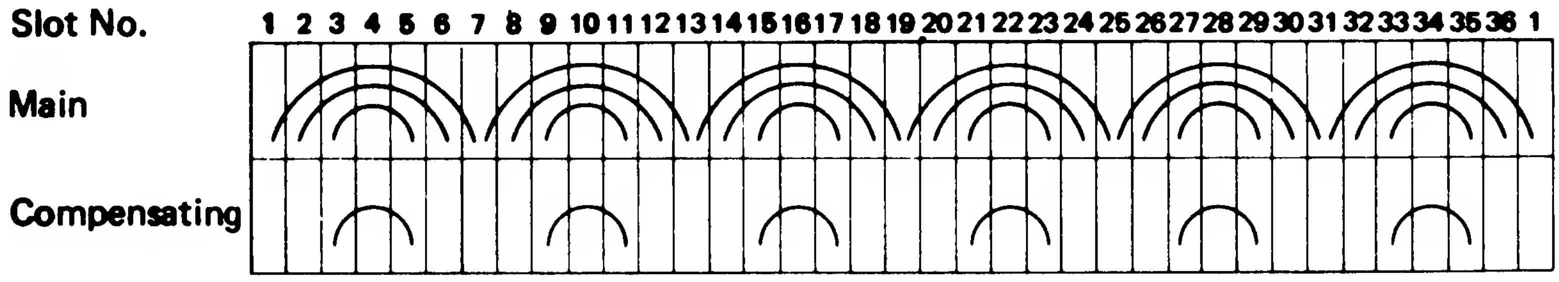


Fig. 2–55. A layout of a six-pole compensated repulsion motor. Note the location of the compensating winding in relation to the main winding. The compensating winding is generally wound into the slots first.

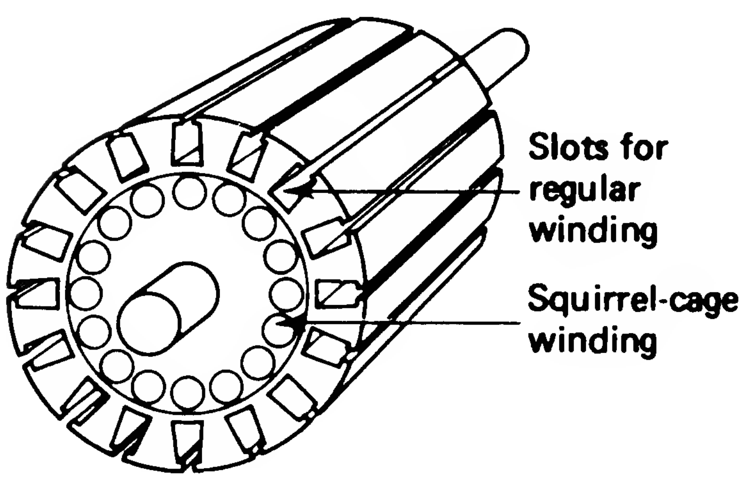


Fig. 2–56. An armature of a repulsion-induction motor. Note slots and squirrel-cage winding.

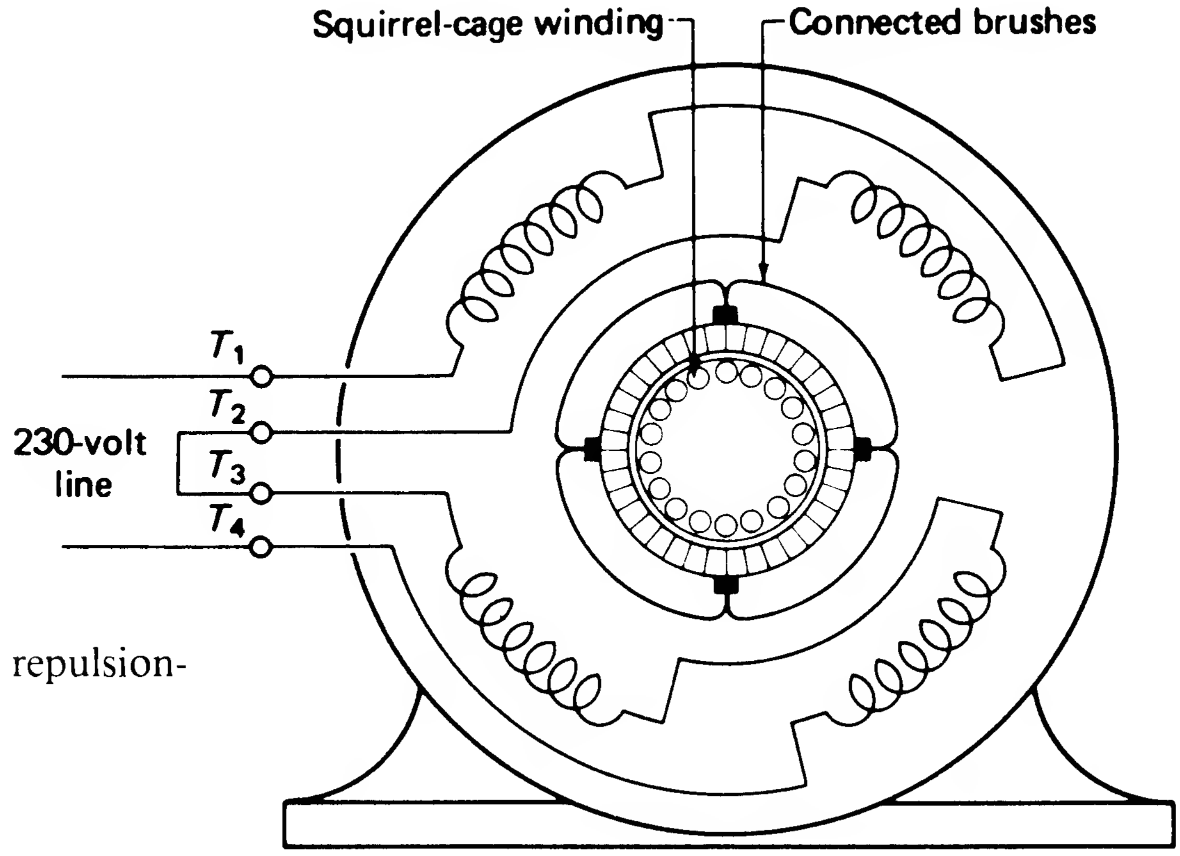


Fig. 2–57. A typical repulsion-induction motor.

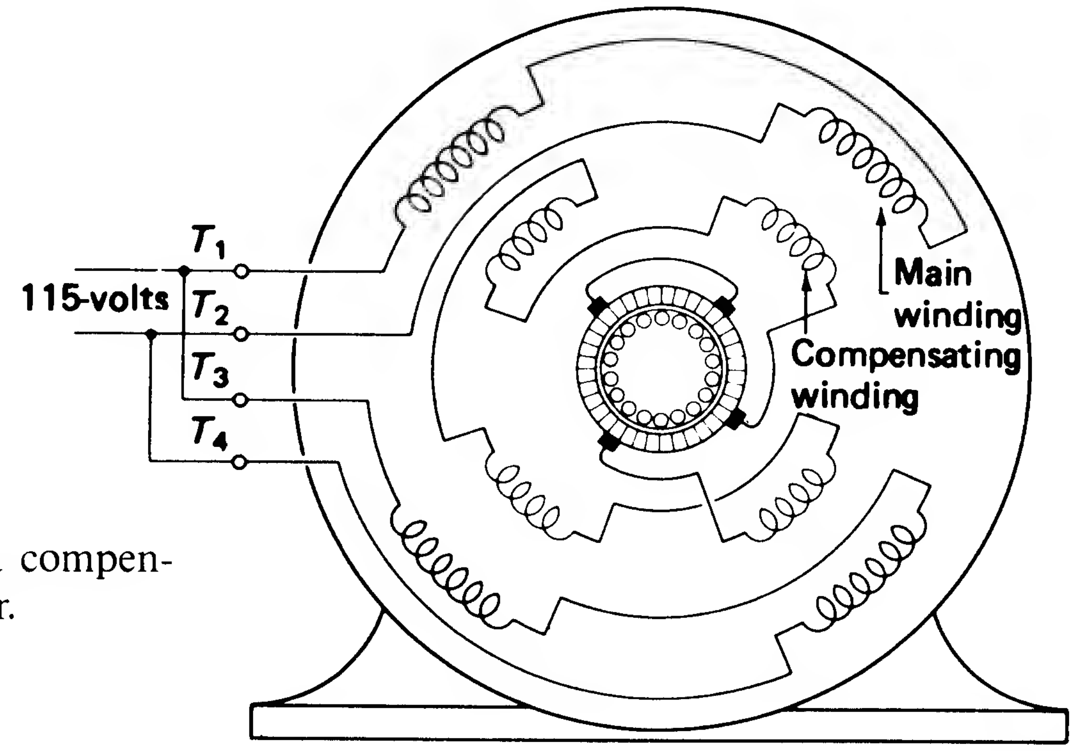
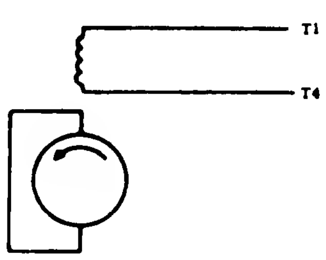


Fig. 2–58. A diagram of a compensated repulsion-induction motor.

MG 1-2.52 Schematic Diagrams for Repulsion, Repulsion-Start Induction and Repulsion-Induction Motors

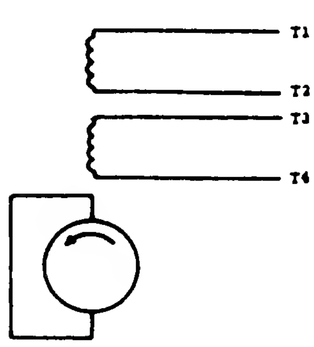
Reversible by Shifting Brushes

Single Voltage



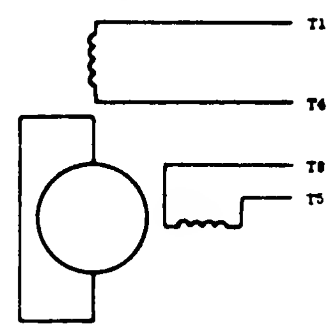
L1 to T1
L2 to T4

Double Voltage

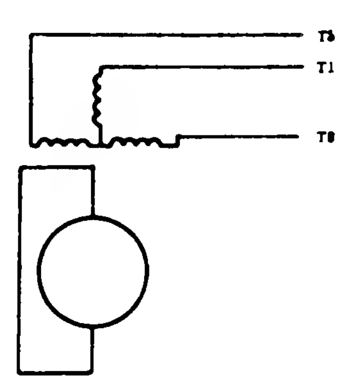


	L1	L2	Join
Higher nameplate voltage	T1	T4	T2, T3
Lower nameplate voltage	T1, T3	T2, T4	

Single Voltage—Externally Reversible



	L1	L2	Join
Counter-clockwise rotation	T1	T5	T4, T8
Clockwise rotation	T1	T8	T4, T5



	L1	L2	Insulate
Counter-clockwise rotation	T1	T5	T8
Clockwise rotation	T1	T8	T5

NEMA Standard 11-16-1967.

Fig. 2–59. Schematic diagrams for repulsion, repulsion-start induction and repulsion-induction motors.

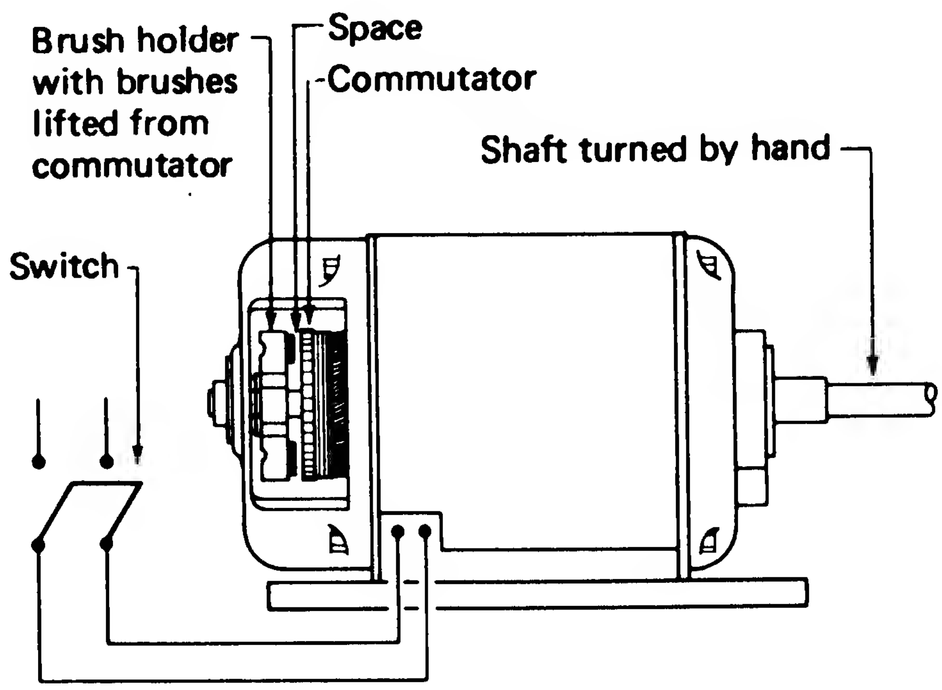


Fig. 2-60. Testing a repulsion motor for a shorted armature. Lift the brushes from the commutator; throw the switch on, and turn the armature by hand. If it turns freely, the armature is not shorted.

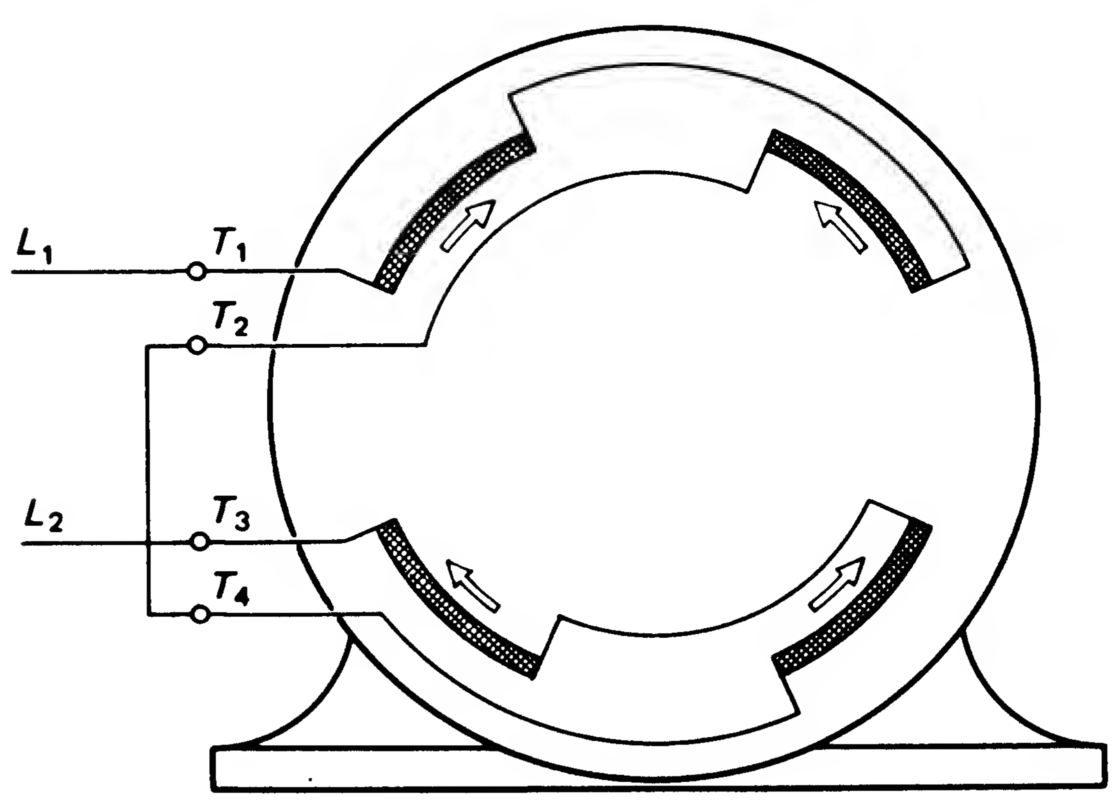


Fig. 2-61. A wrong connection for 230 volts. The current flows through two adjacent poles in the same direction. The motor hums and does not run. To remedy, connect T_2 and T_3 together, L_1 to T_1 and T_4 to L_2.

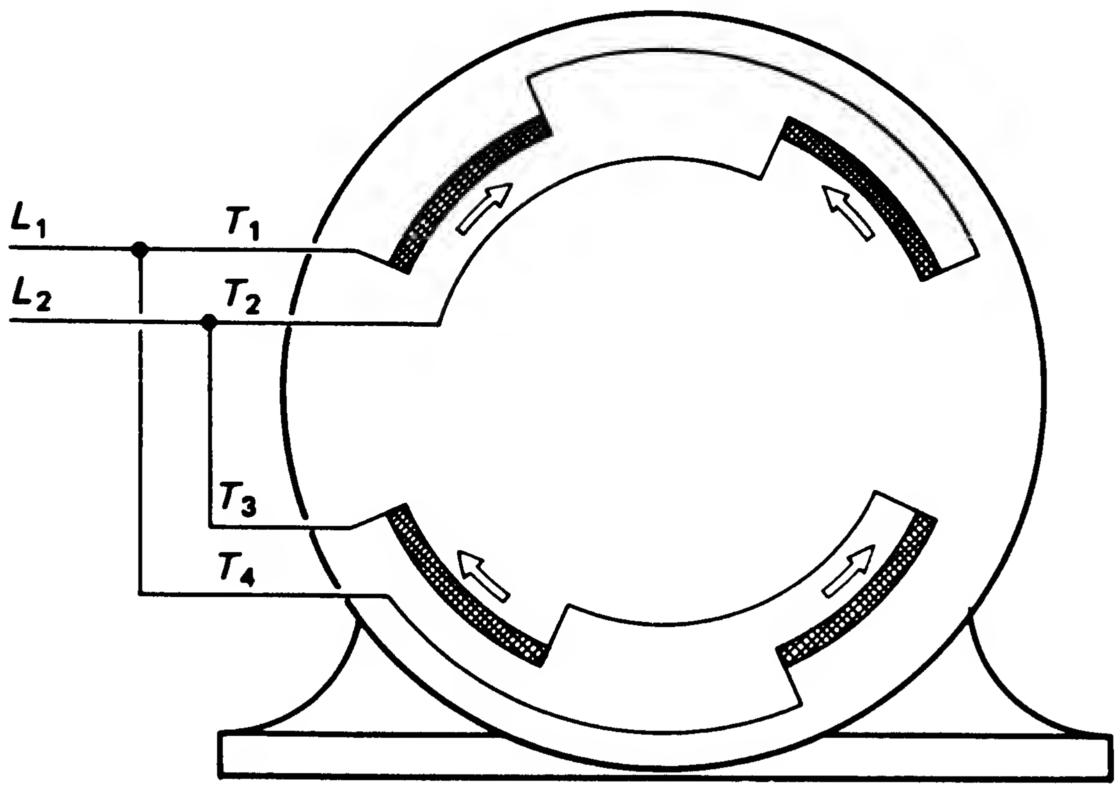


Fig. 2–62. Although connected for 115 volts, adjacent poles have the same polarity. Remedy by connecting T_1 and T_3 to L_1 and T_2 and T_4 to L_2.

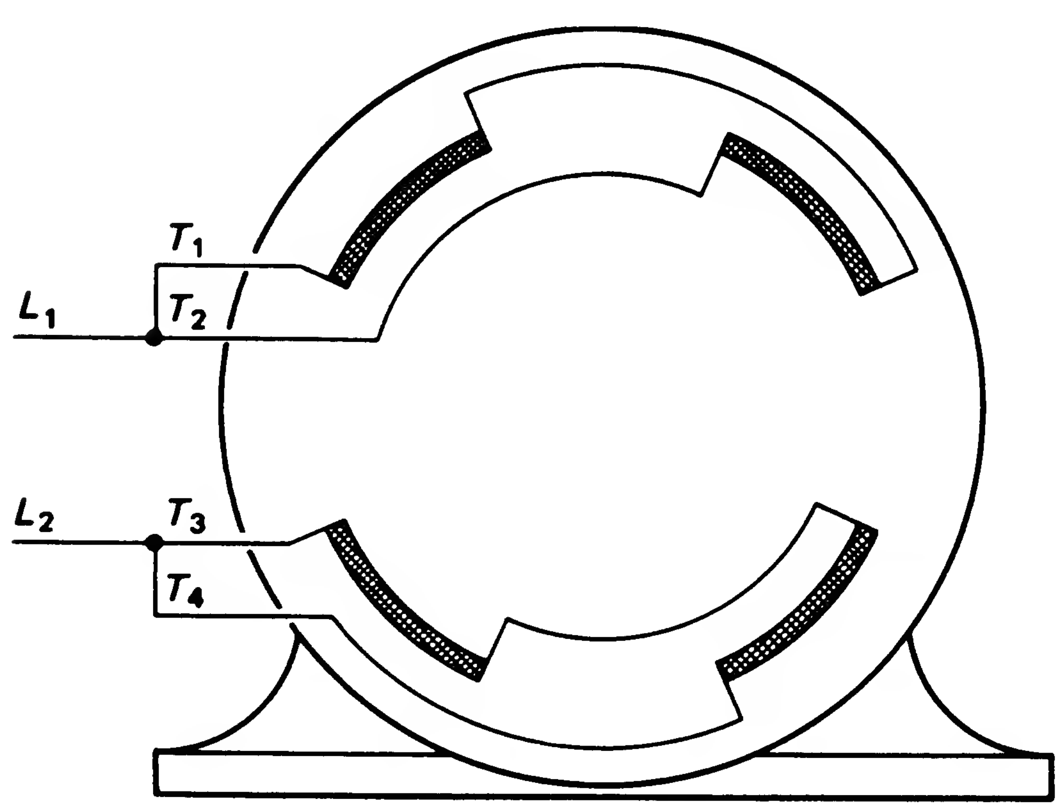


Fig. 2–63. A common mistake. There is no complete circuit across the line, and the motor neither operates nor hums.

CHAPTER 3

Three-phase Motors

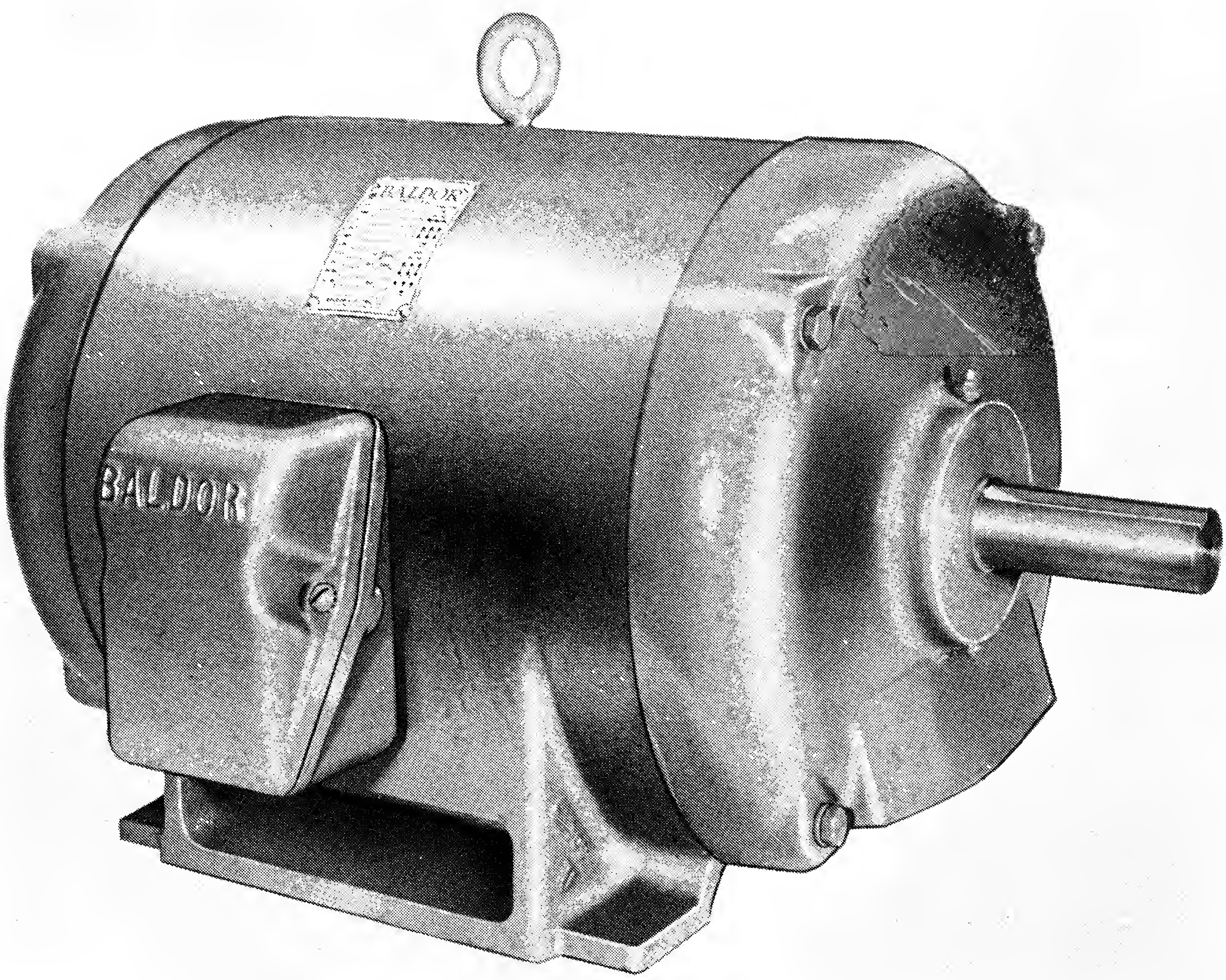


Fig. 3–1. A three-phase motor. *(Baldor Electric Co.)*

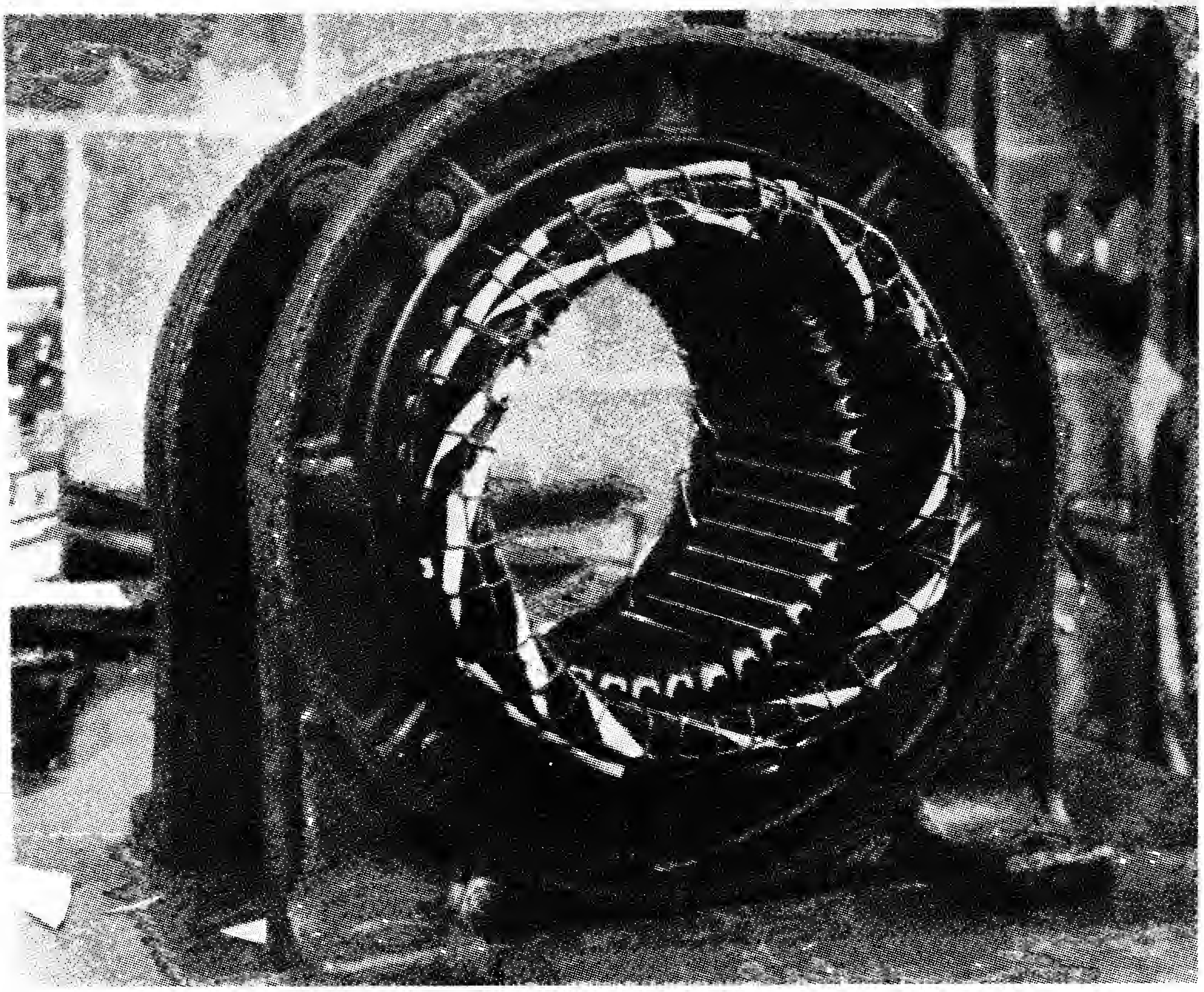


Fig. 3–2. A stator of a three-phase motor. *(Lenni Products)*

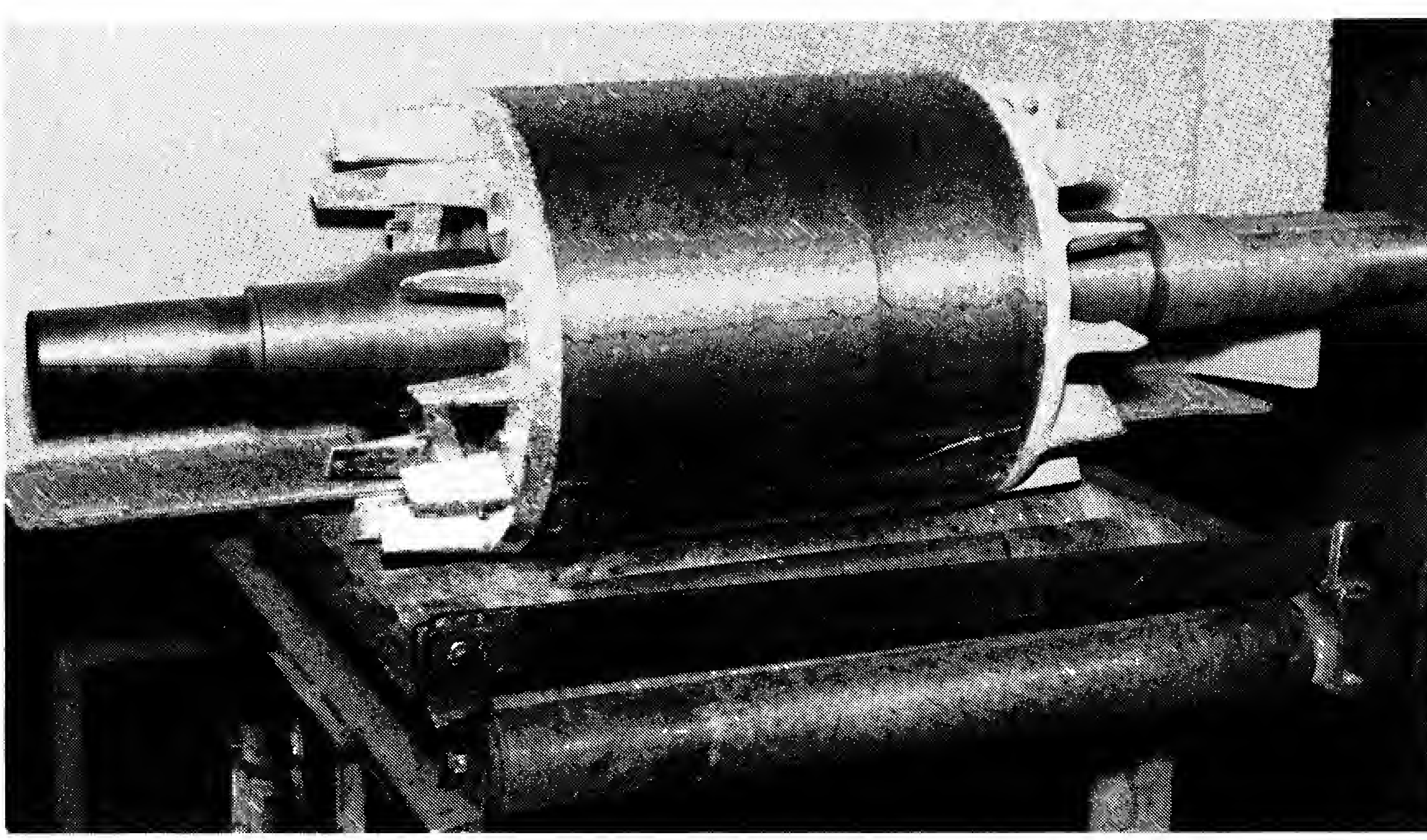


Fig. 3–3. Rotor of a three-phase motor. *(Westinghouse Electric Co.)*

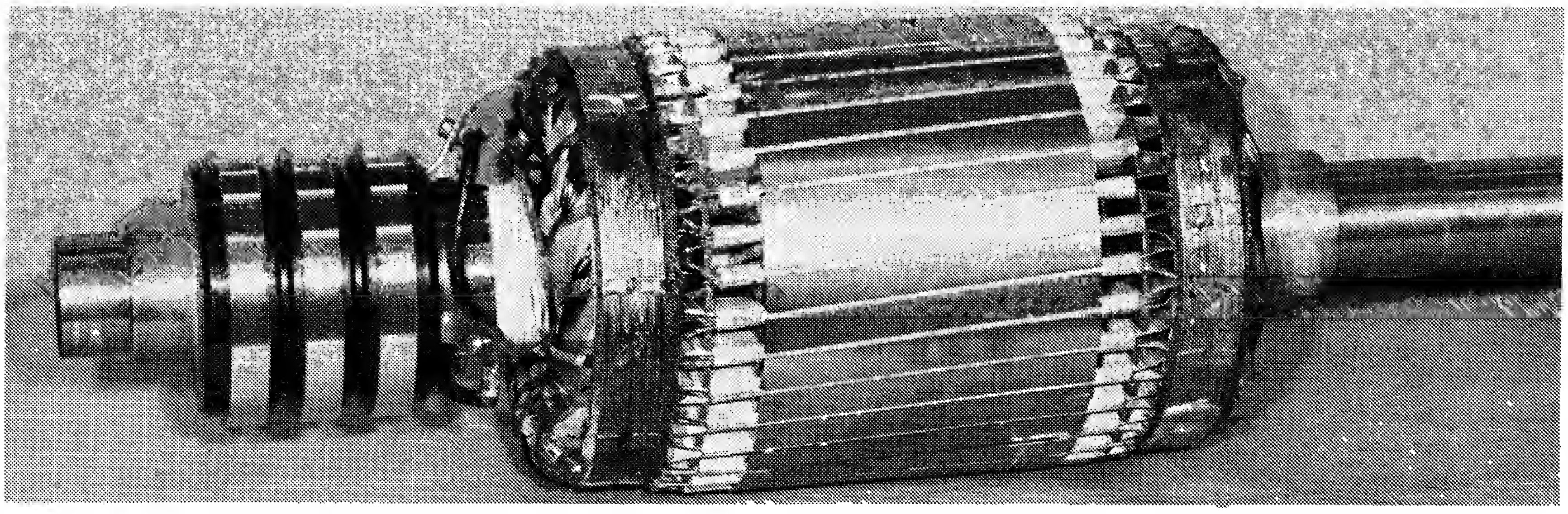


Fig. 3-4. A wound rotor of a three-phase motor. *(Westinghouse Electric Co.)*

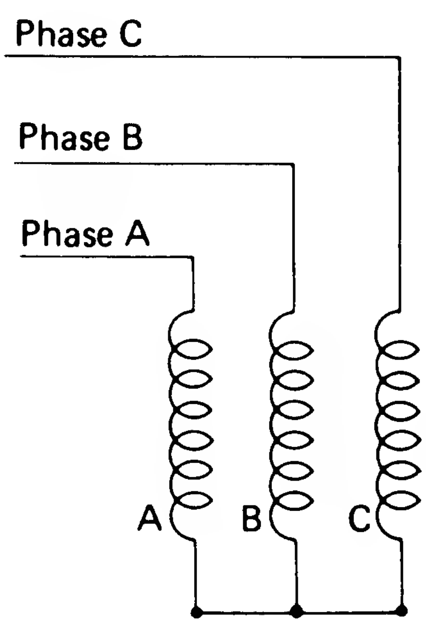
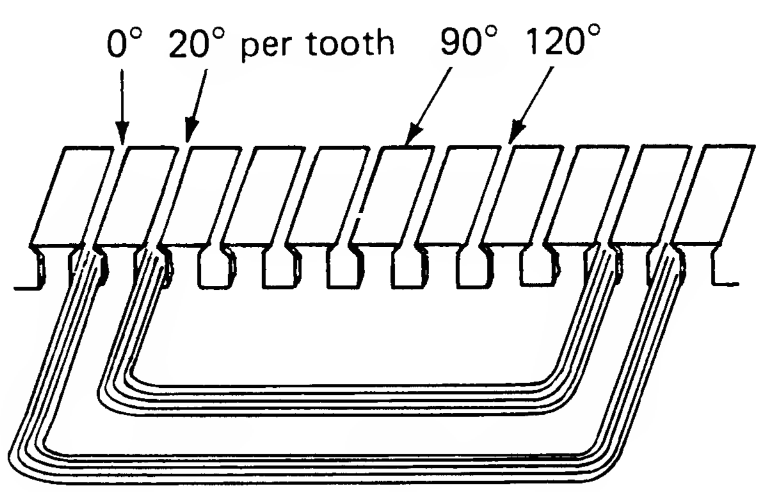


Fig. 3-5. The coils of a three-phase motor connected to produce three windings, or phases.

Fig. 3-6a. A four-pole, 36-slot stator. Each tooth equals 20°. This is a concentric-wound coil group showing the 90° and the 120° locations. The 120° slot is where the first coil of the next phase group with the same polarity is placed.



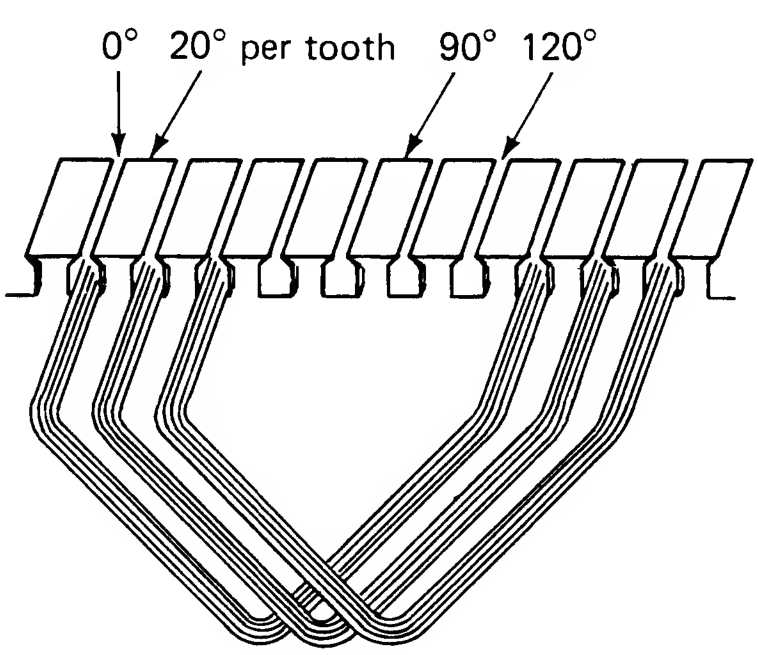
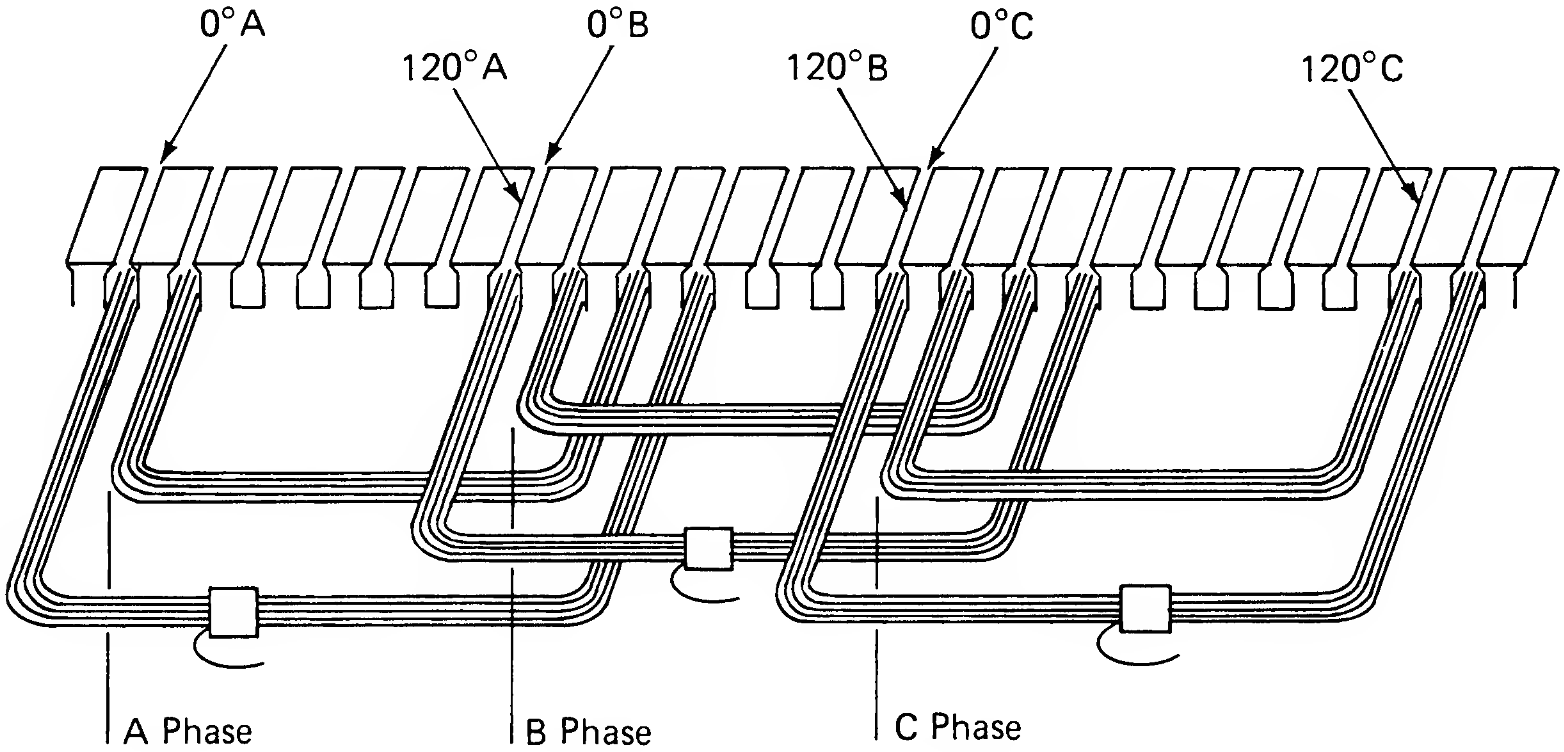


Fig. 3-6b. A lap-wound coil group showing the 90° and the 120° location. The 120° slot is where the first coil of the next phase group with the same polarity is placed.



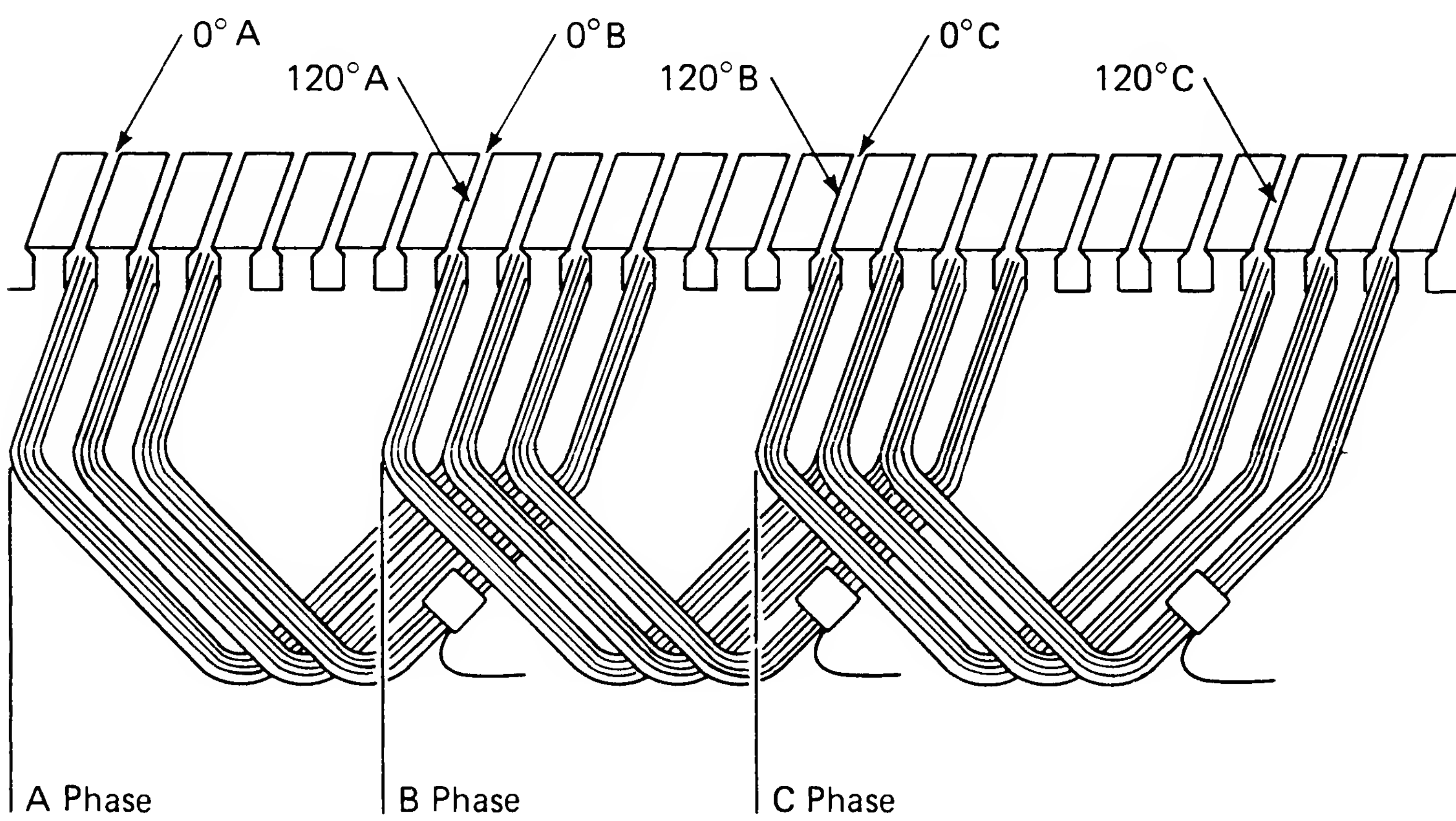


Fig. 3–7. Concentric and lap coil placement 120° apart. Each coil group is the start of its phase and is of the same polarity.

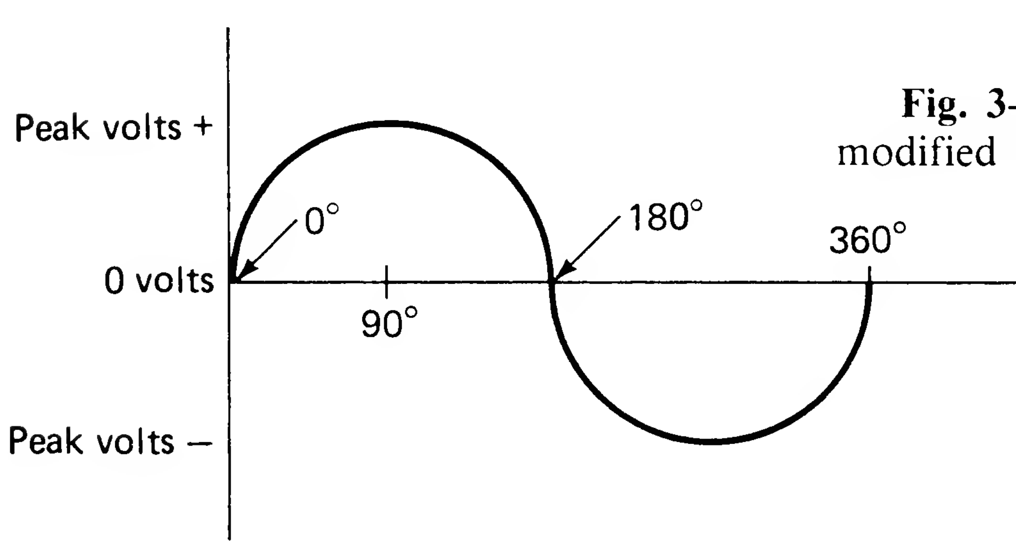


Fig. 3–8. The single-phase sine wave modified for illustration purposes.

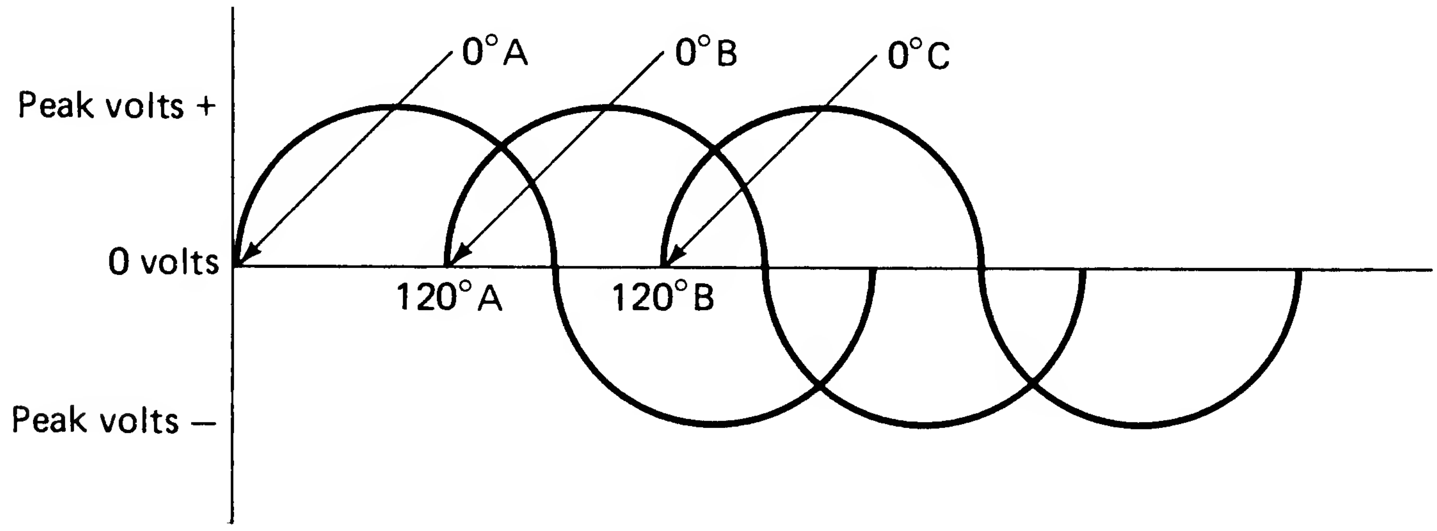


Fig. 3–9. A simplified three-phase sine wave showing where each phase starts.

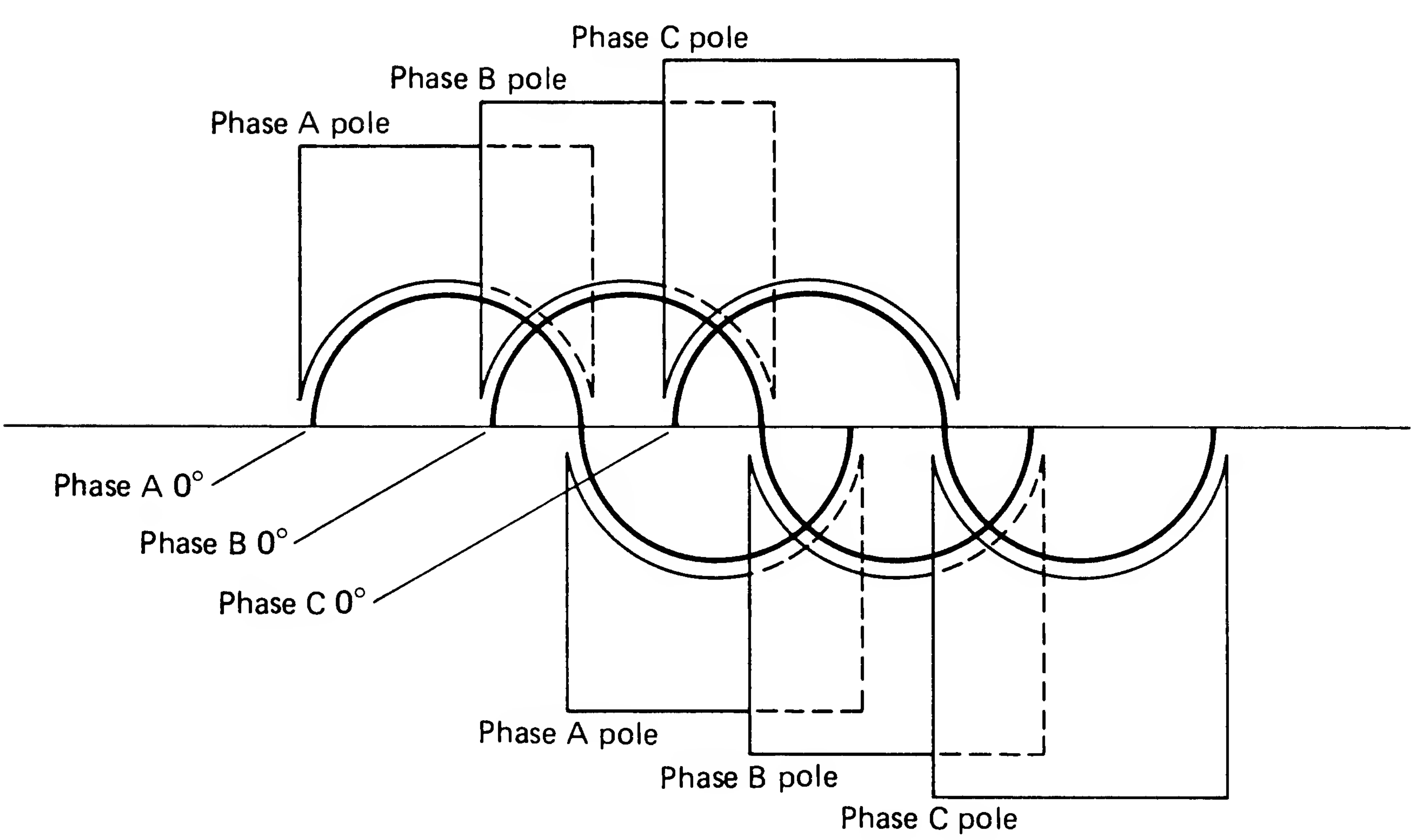


Fig. 3–10. Illustration of how the coil groups or poles of a three-phase stator fit the three-phase sine wave.

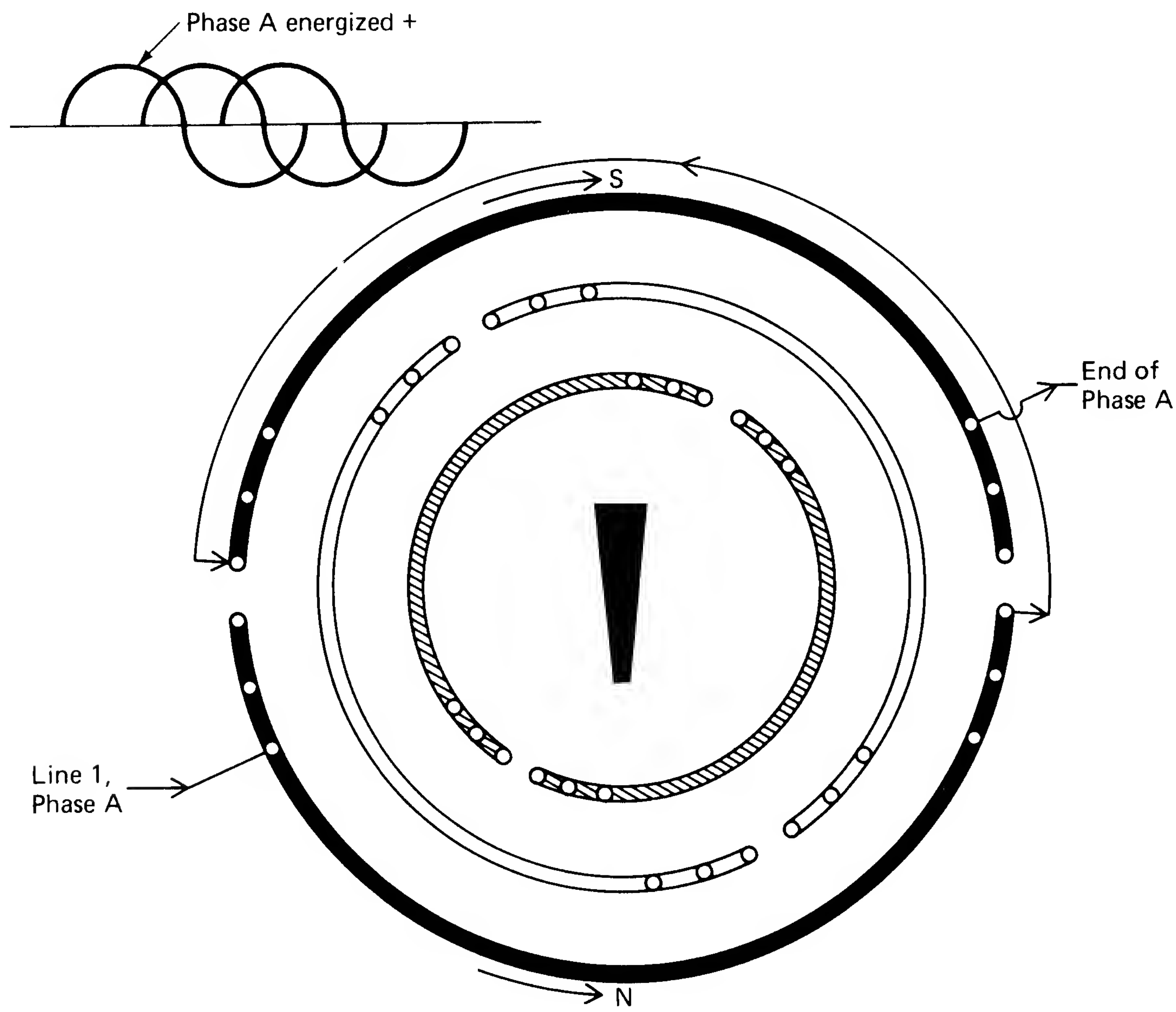


Fig. 3-11a. The A phase is energized as shown on sine wave, setting up a polarity in the stator that attracts the bar magnet.

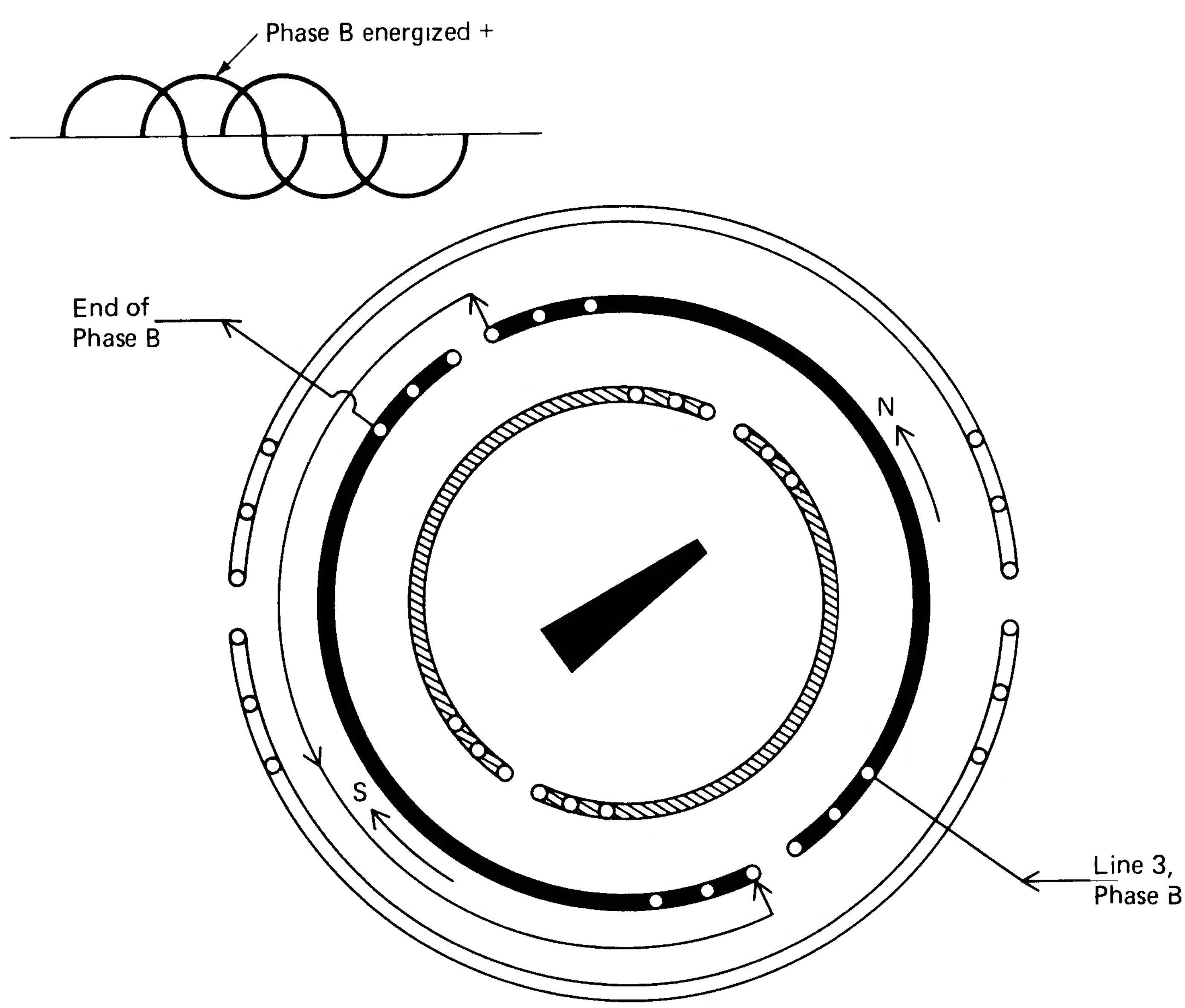


Fig. 3-11b. The B phase is energized, attracting the magnet as shown.

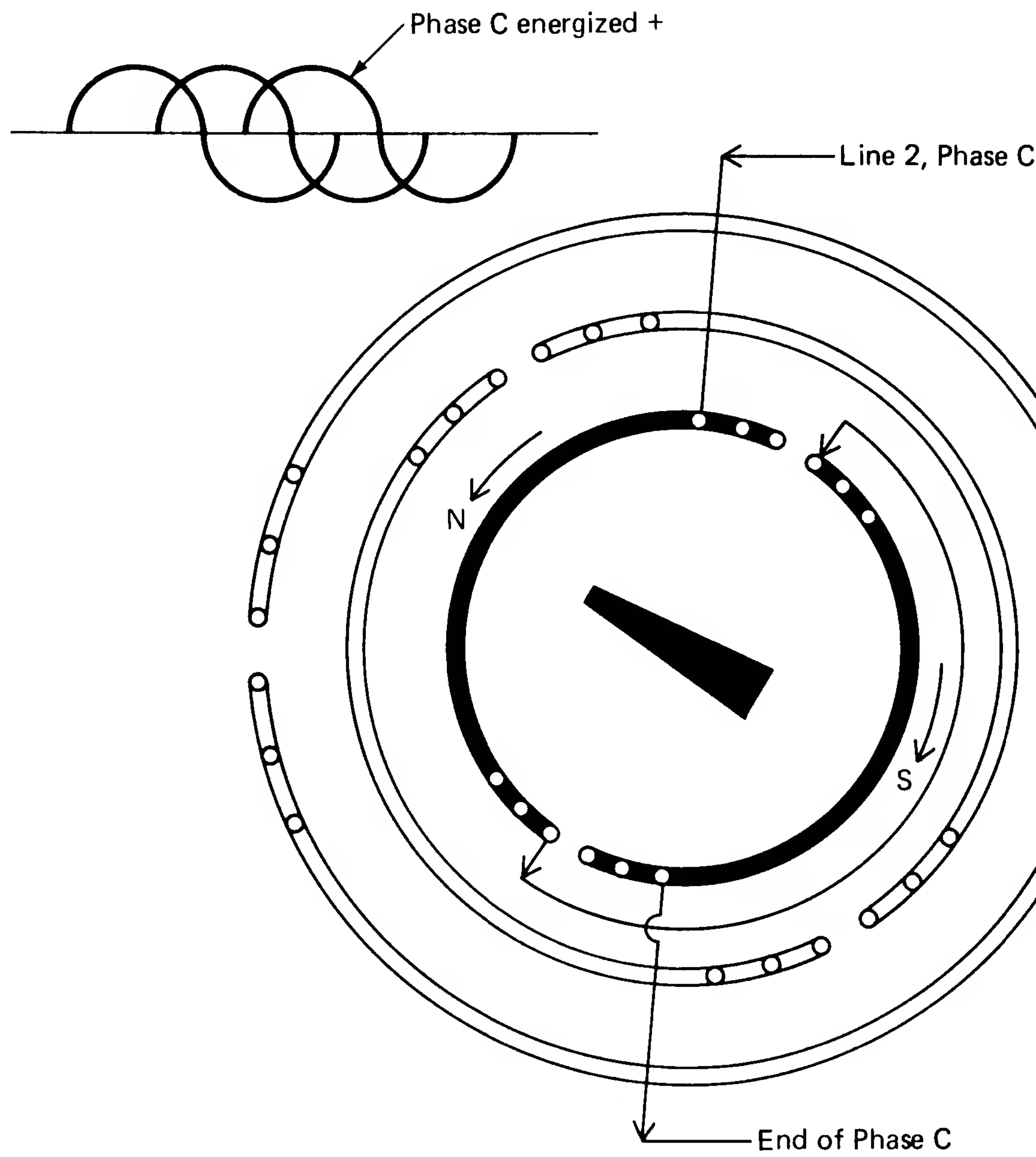


Fig. 3-11c. The C Phase is energized, attracting the magnet in this position.

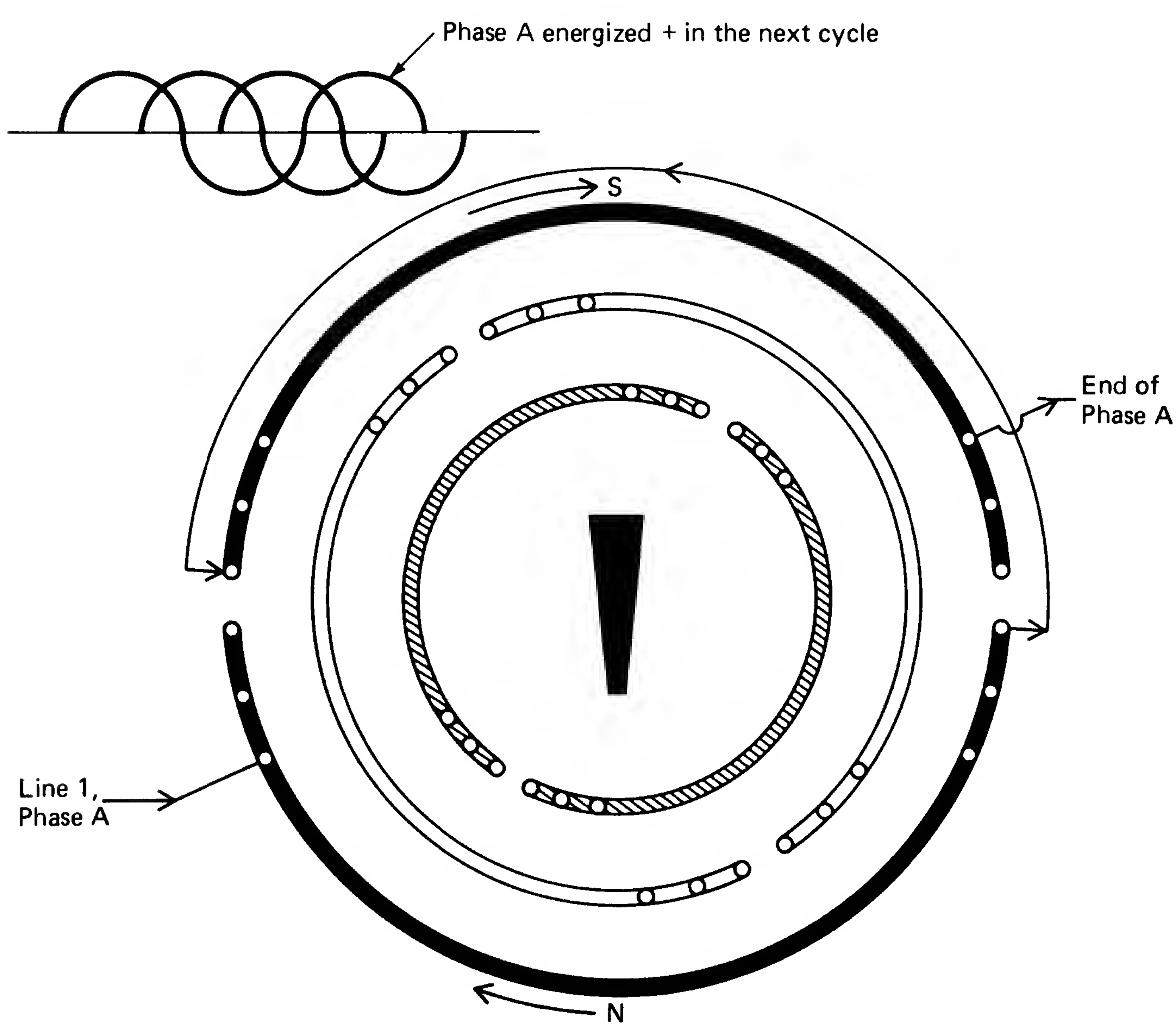


Fig. 3-11d. The A phase energized the same as in **Fig. 3-11a** to complete one revolution.

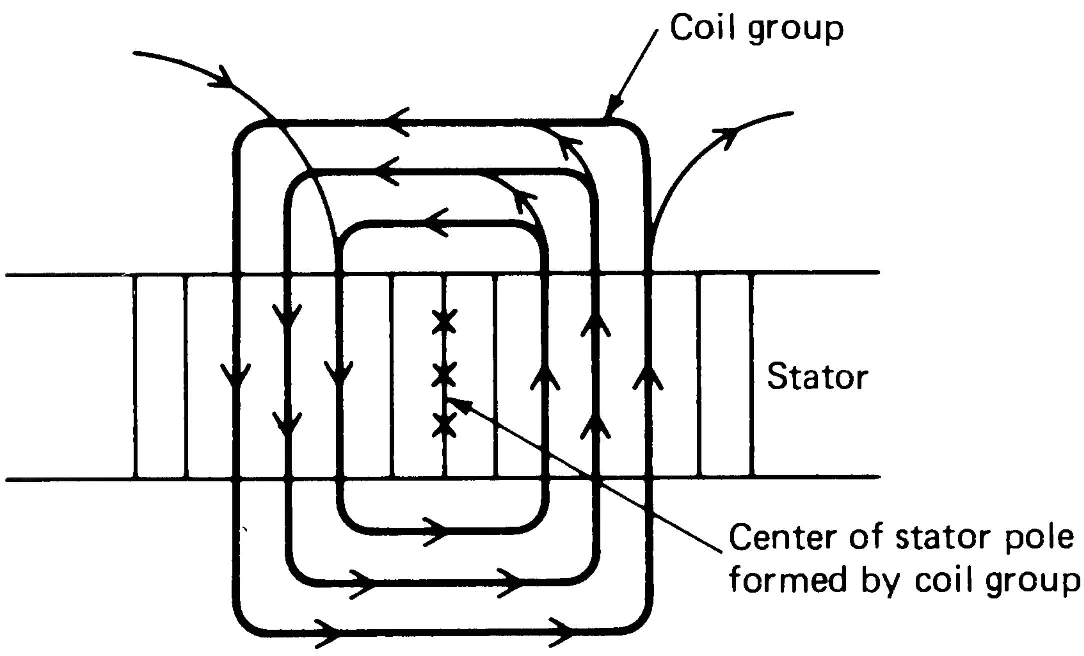


Fig. 3-12. Pole formed in the stator by the current in a coil group.

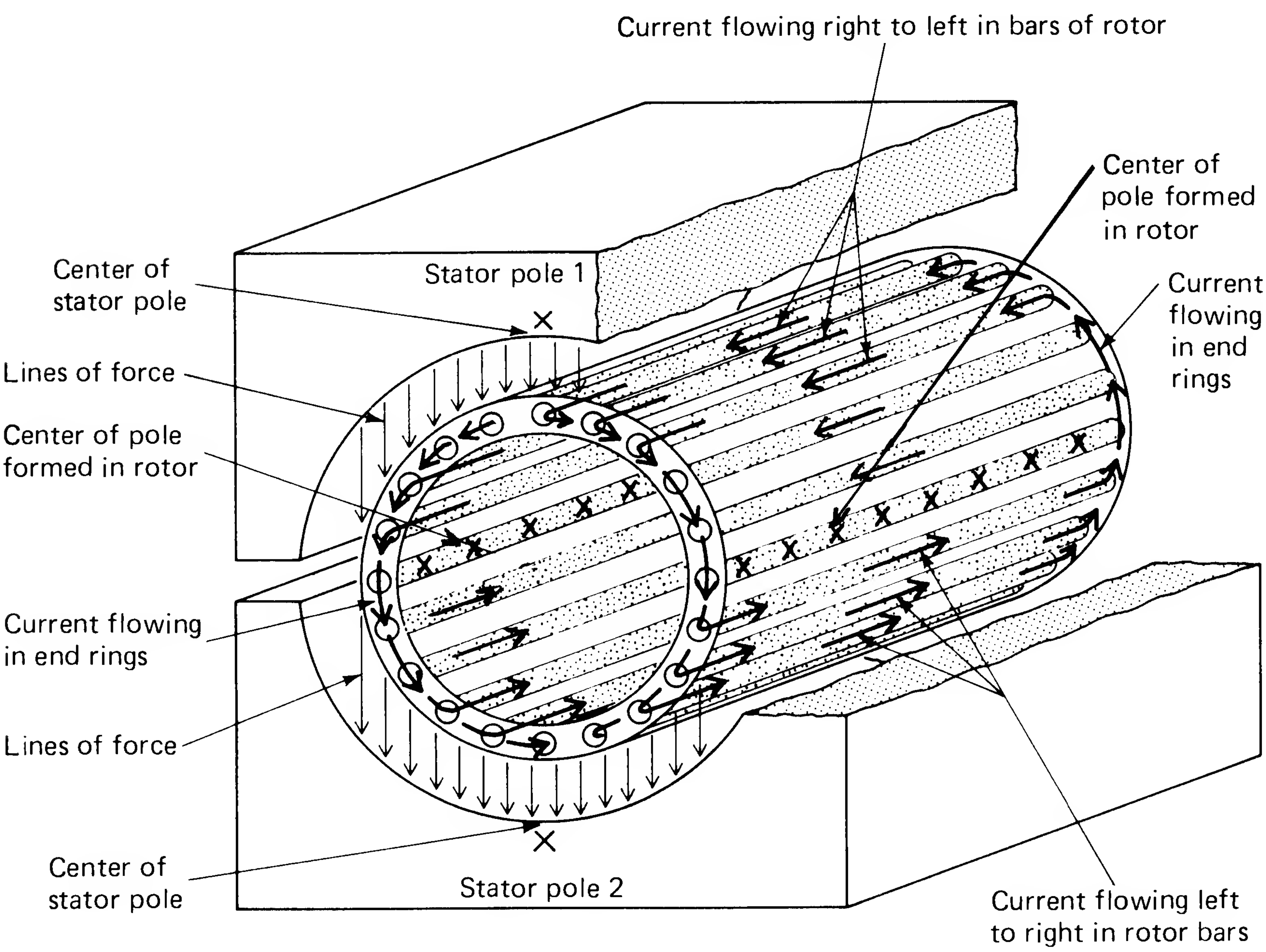


Fig. 3-13. Current flowing in rotor bars at 98 percent rpm. Bars located at 90° from the stator pole centers are the center of the rotor poles.

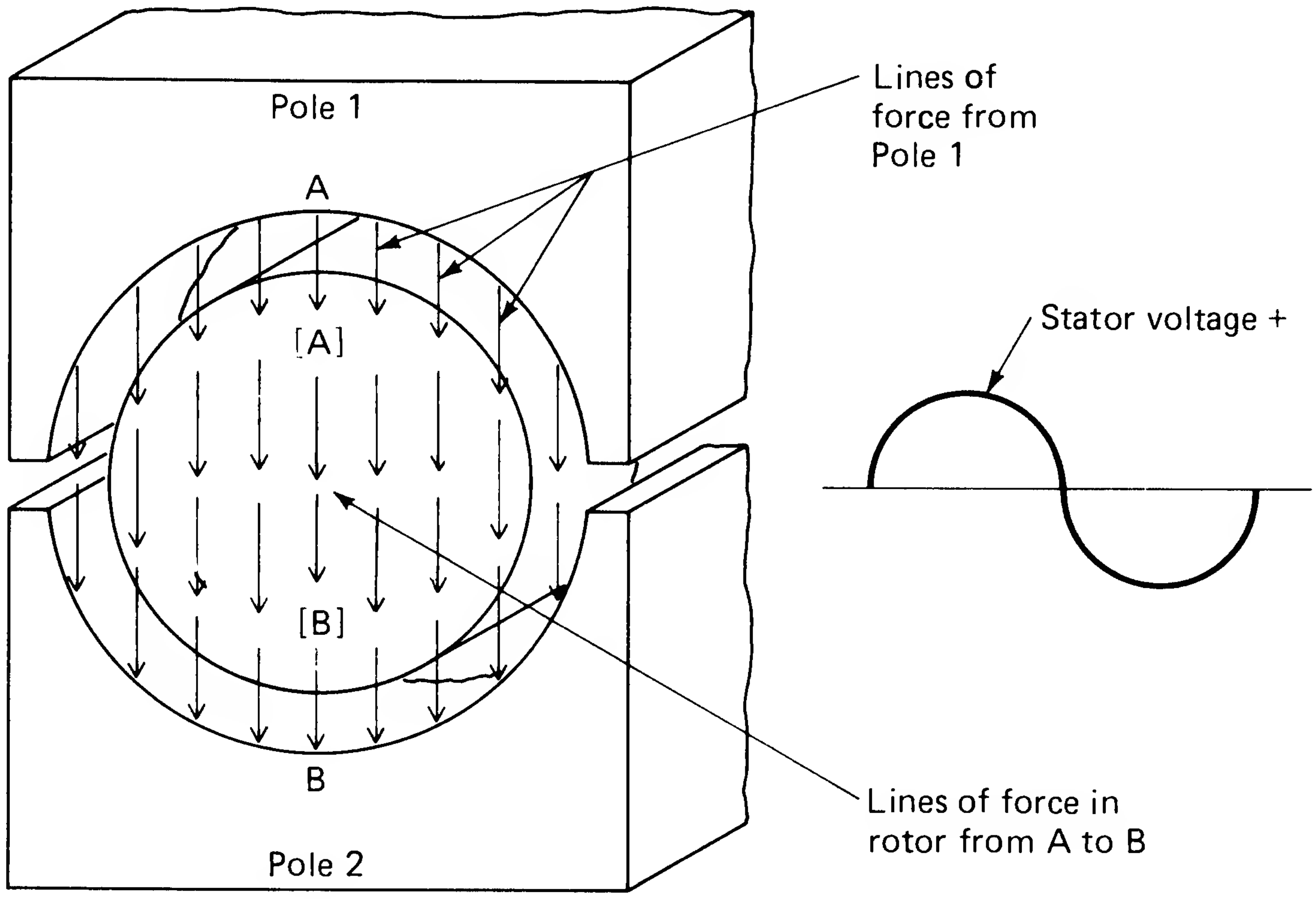


Fig. 3–14a. Magnetic lines of force going through the rotor at synchronous speed.

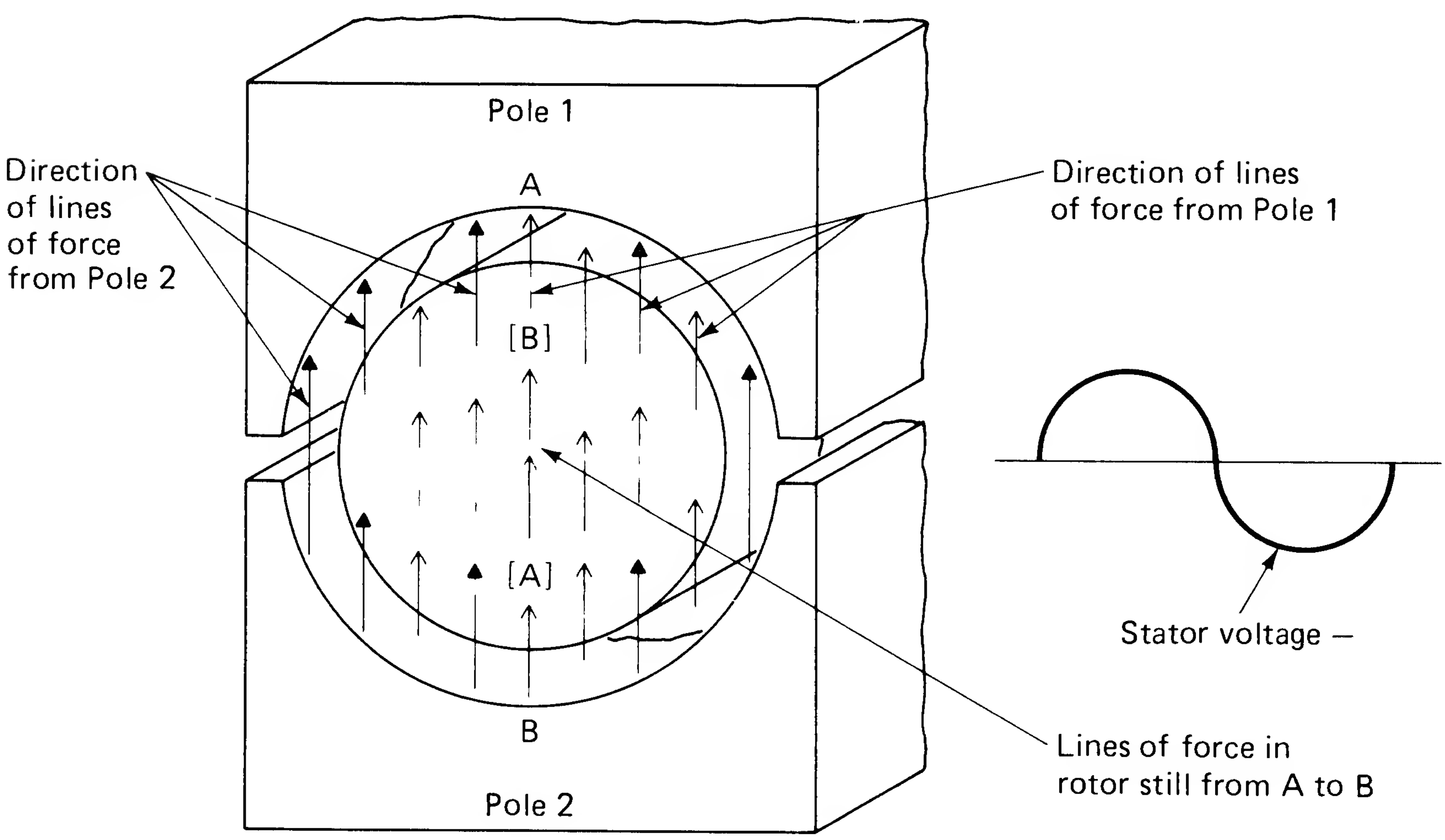


Fig. 3–14b. By the time the polarity reverses in the stator, the rotor has rotated to a position where it needs no magnetic reversal. The magnetic lines of force continue to flow through it in the same direction.

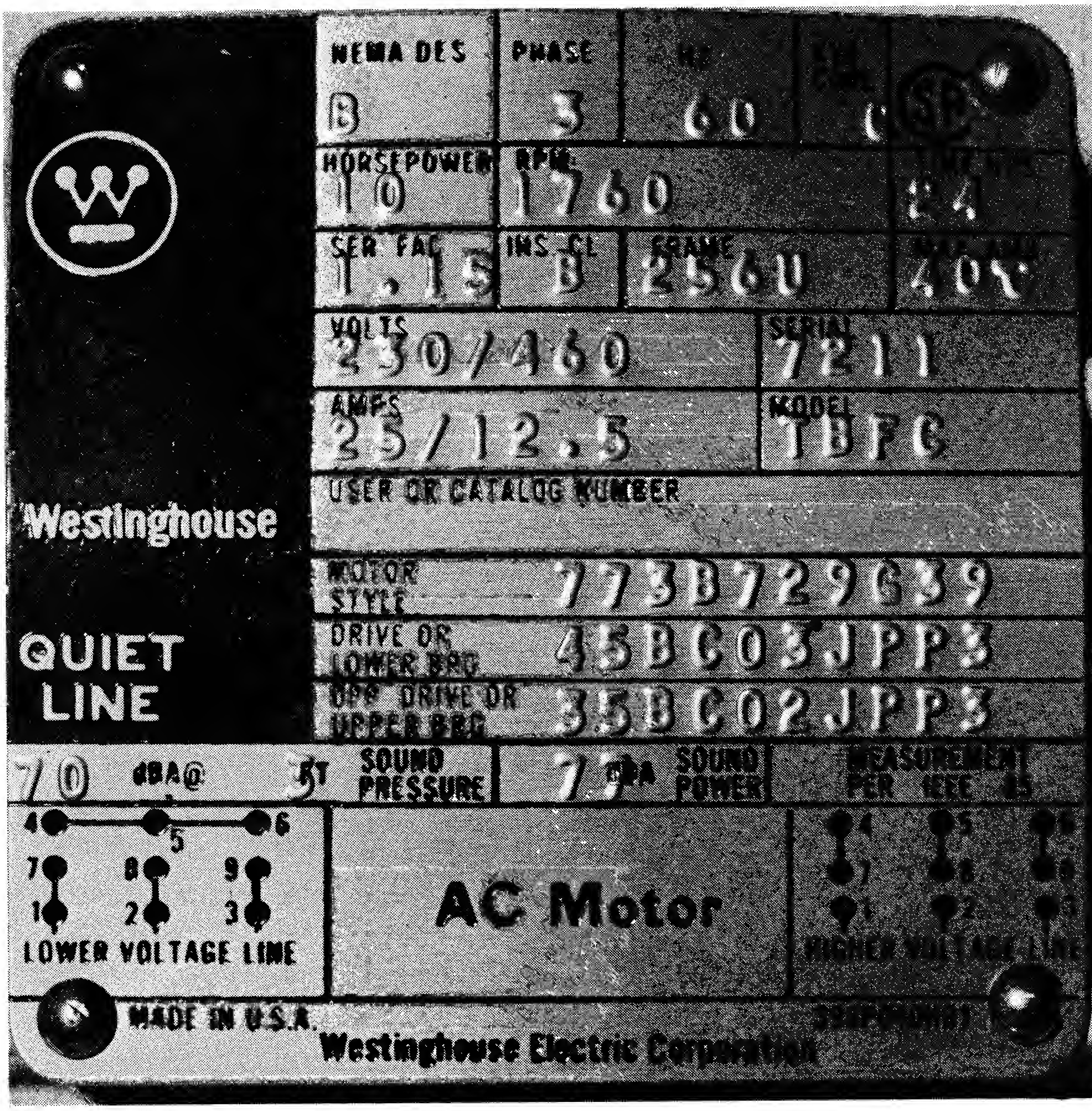


Fig. 3-15. Nameplate. *(Westinghouse Electric Co.)*

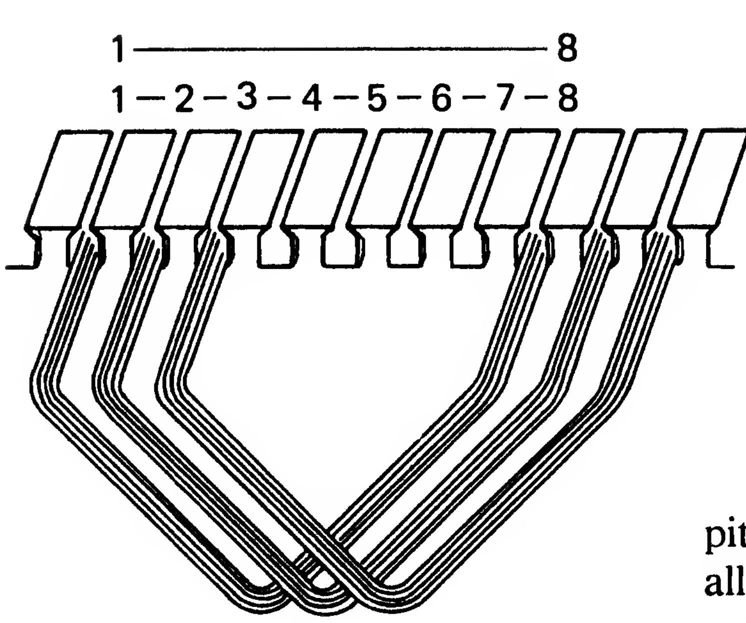


Fig. 3-16. How to count the span or pitch of a coil. The coils in lap windings all have the same span.

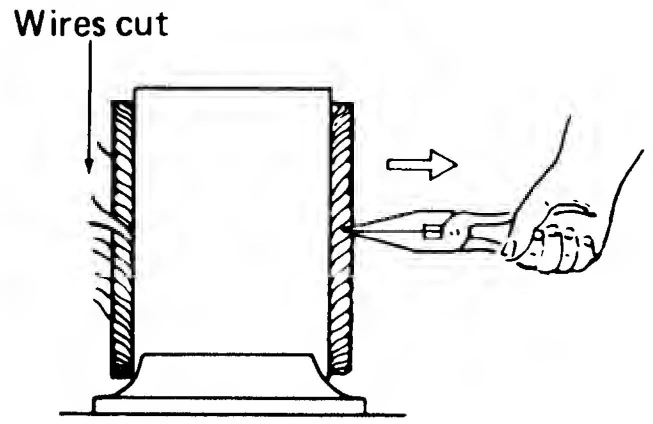


Fig. 3-17. Stripping the stator by cutting each coil on one side and pulling from the other side.

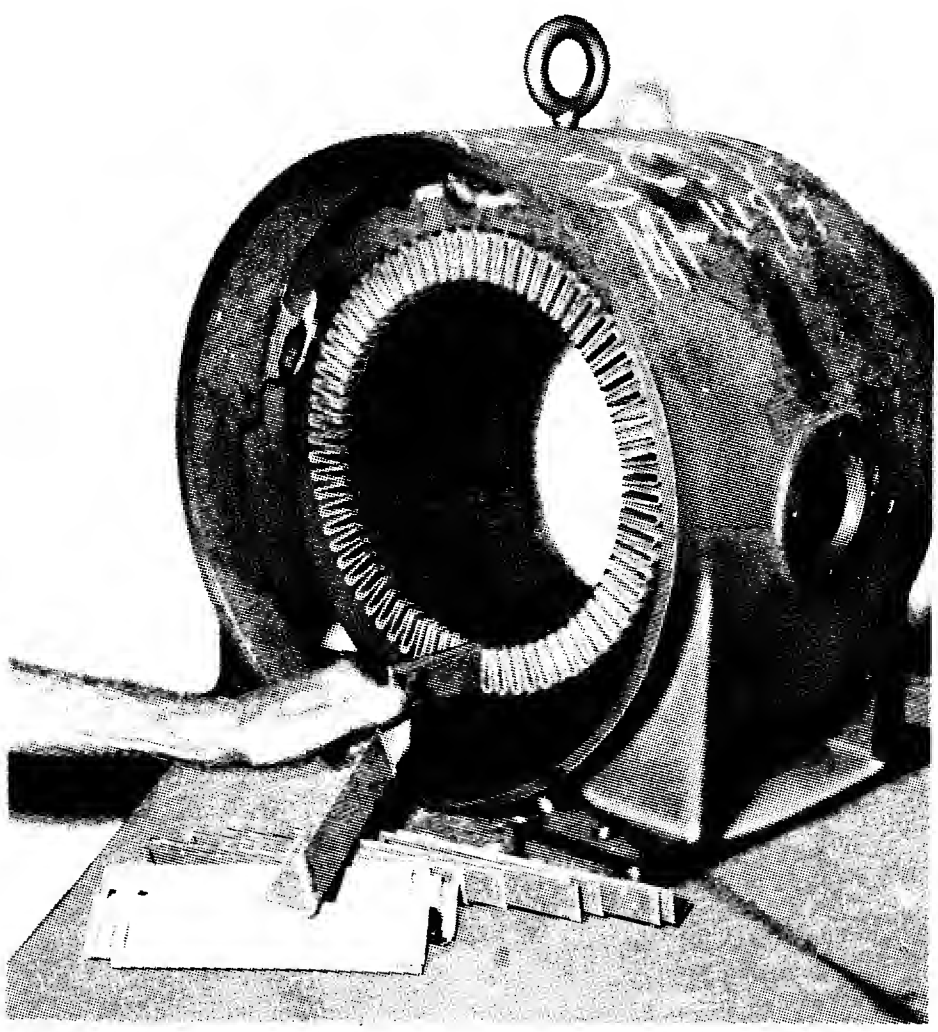


Fig. 3-18. Motor using cuffed insulation in slots. *(Wagner Electric Company)*

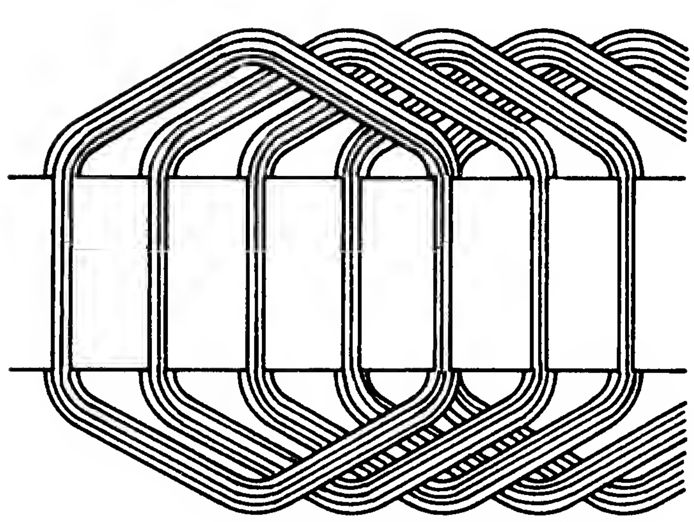


Fig. 3-19. A partial view of the coils in the slots of a lap winding.

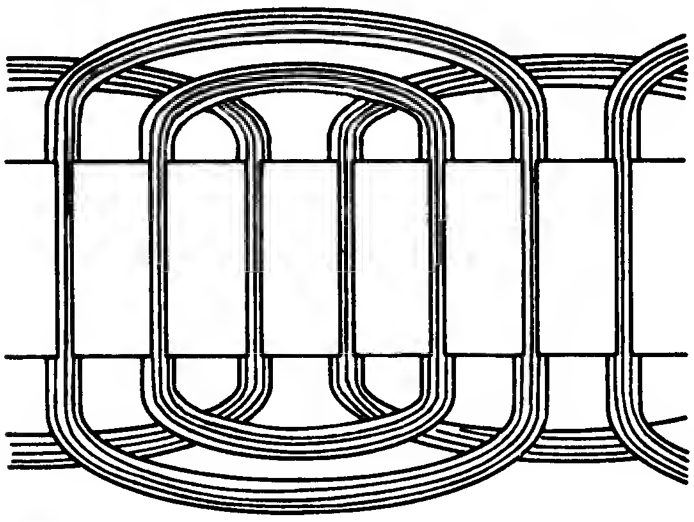


Fig. 3–20. A partial view of the coils in the slots of a concentric or chin winding.

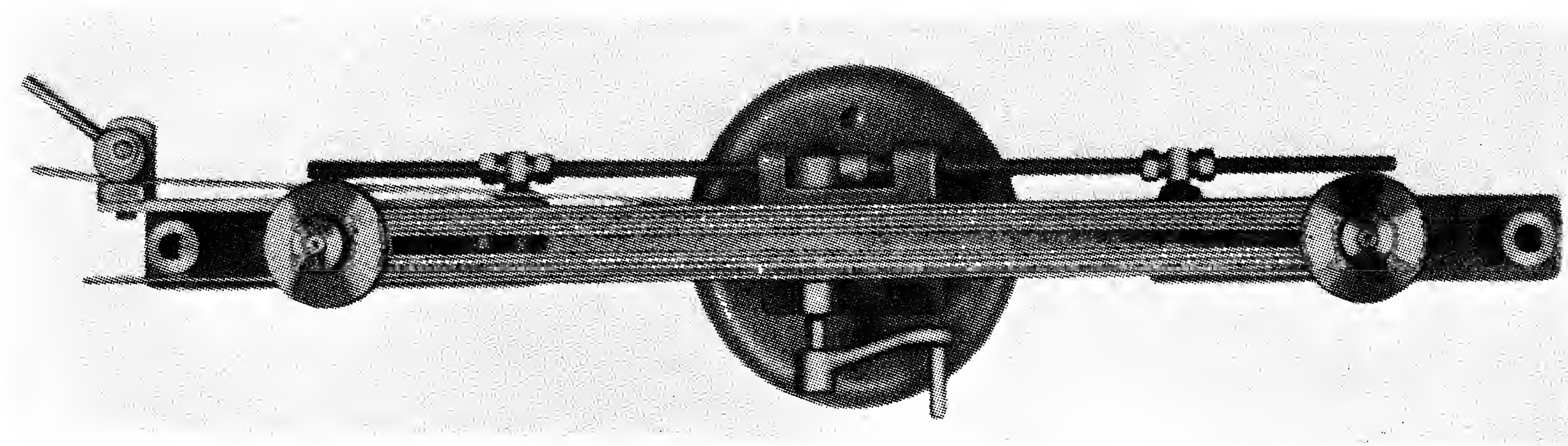
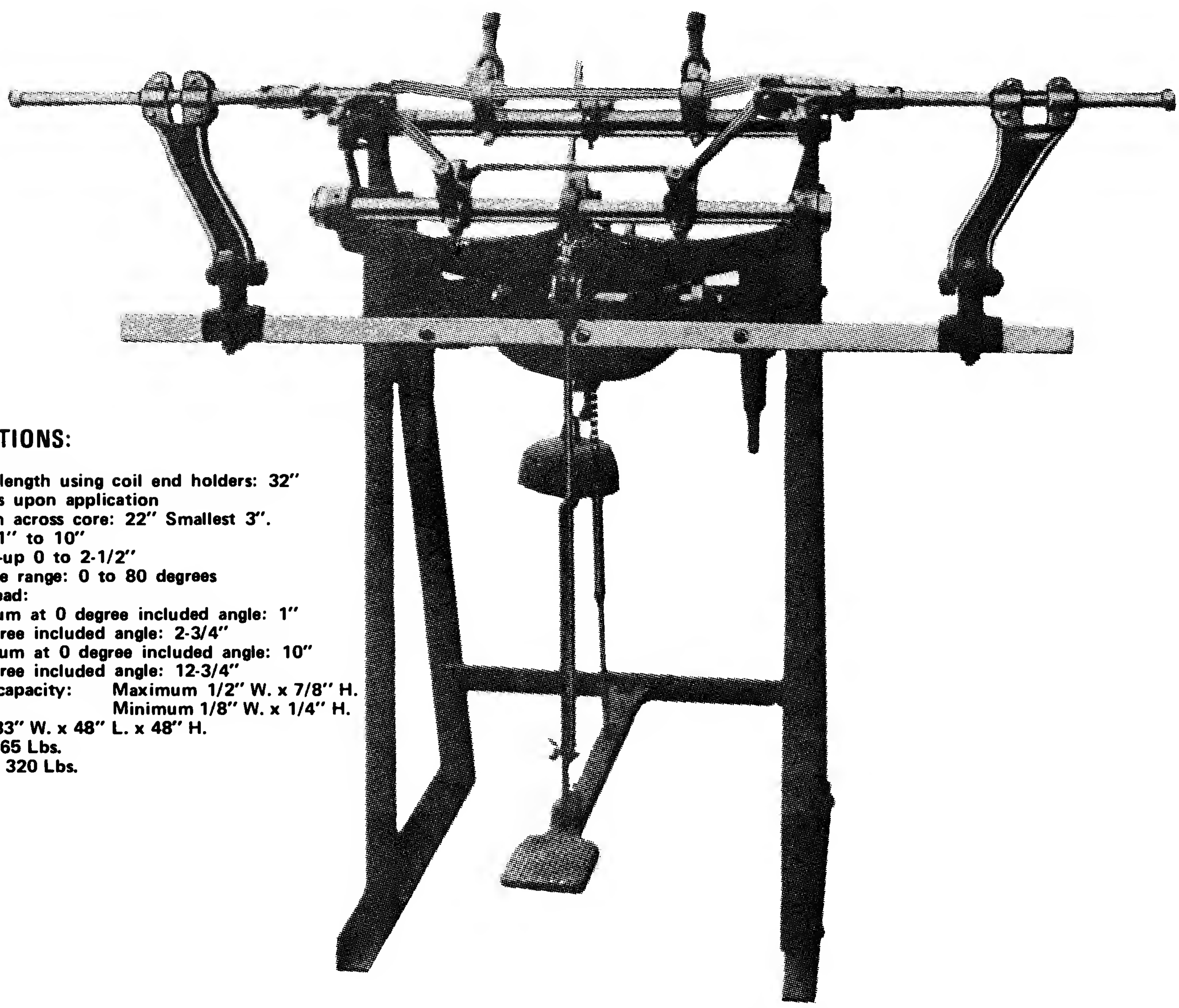


Fig. 3–21. A loop-forming head for formed coils. *(Armature Coil Equipment, Inc.)*



SPECIFICATIONS:

Largest loop length using coil end holders: 32"
Larger lengths upon application
Largest length across core: 22" Smallest 3".
Coil spread: 1" to 10"
Knuckle kick-up 0 to 2-1/2"
Included angle range: 0 to 80 degrees
Width of spread:
  Minimum at 0 degree included angle: 1"
  80 degree included angle: 2-3/4"
  Maximum at 0 degree included angle: 10"
  80 degree included angle: 12-3/4"
Jaw holding capacity: Maximum 1/2" W. x 7/8" H.
  Minimum 1/8" W. x 1/4" H.
Dimensions: 33" W. x 48" L. x 48" H.
Net Weight: 265 Lbs.
Gross Weight: 320 Lbs.

Fig. 3–22. A coil-forming machine. *(Armature Coil Equipment, Inc.)*

Figures 3–20; 3–21; 3–22

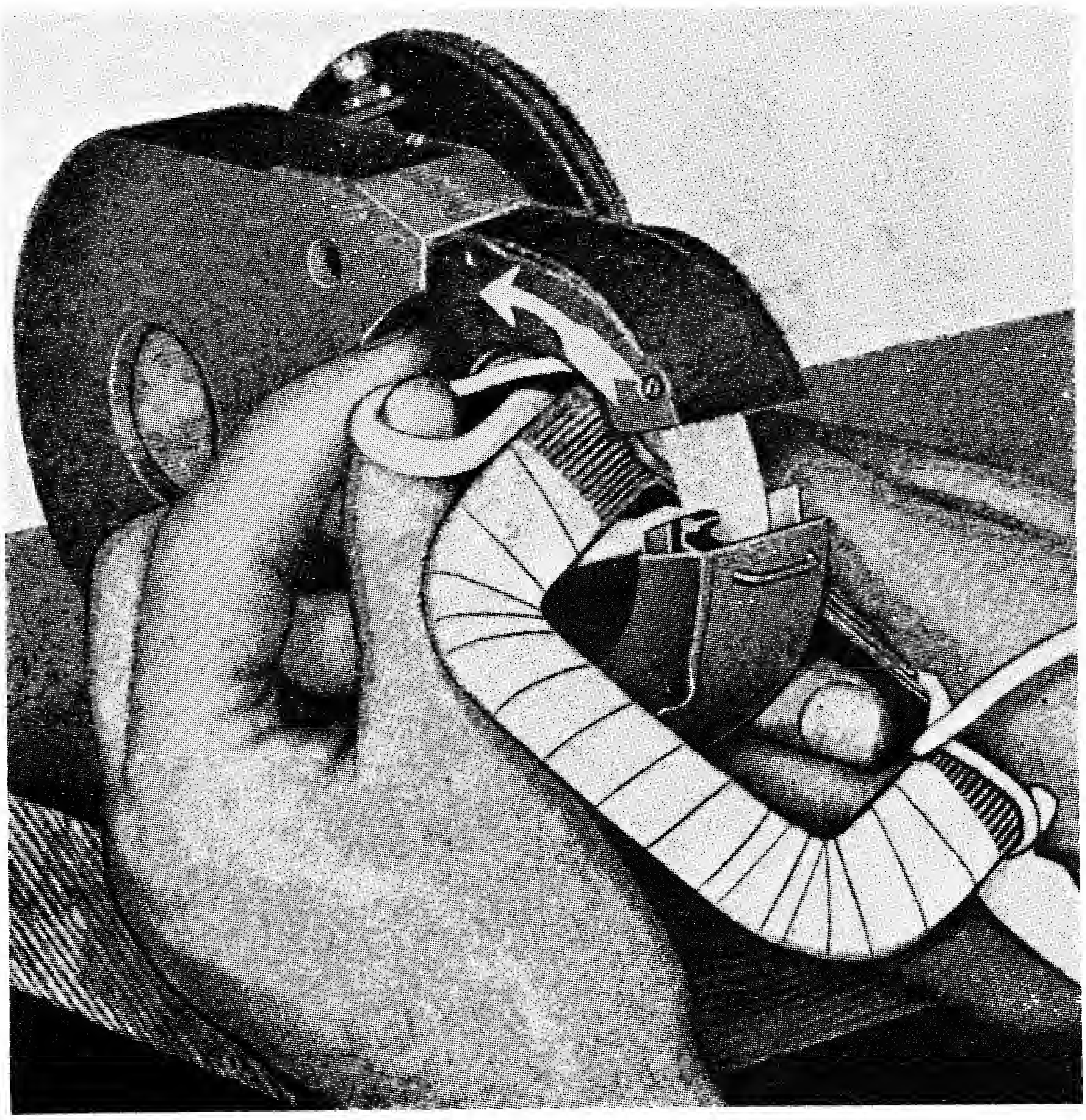


Fig. 3-23. A taping machine. *(P. E. Chapman Electrical Works)*

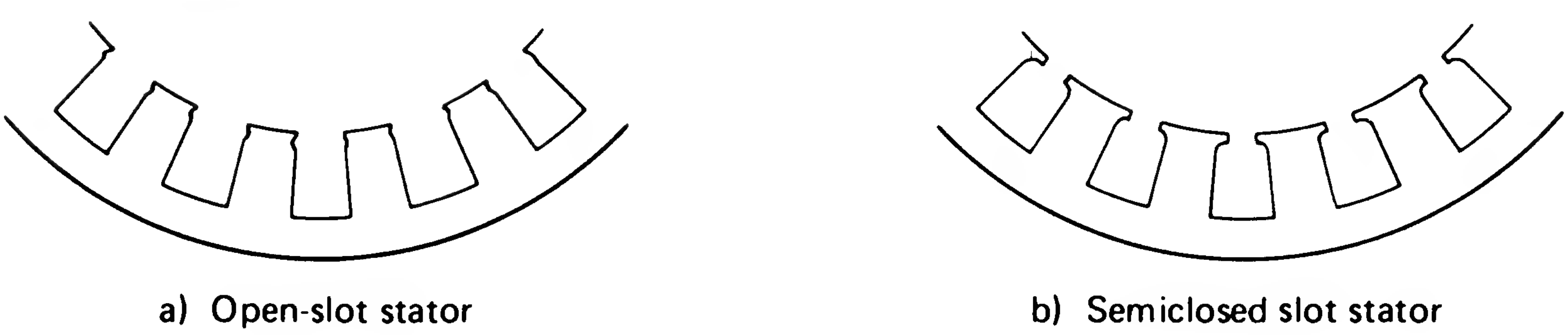


Fig. 3-24. Two types of slots found in the stators of three-phase motors.

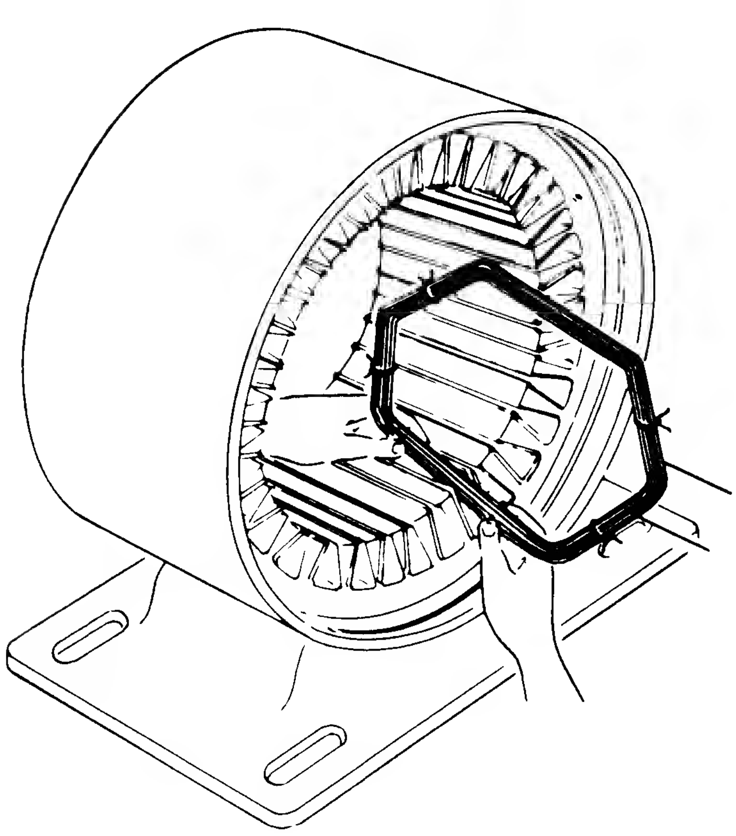


Fig. 3-25. One side of a coil spread so that it can be fed into the slot.

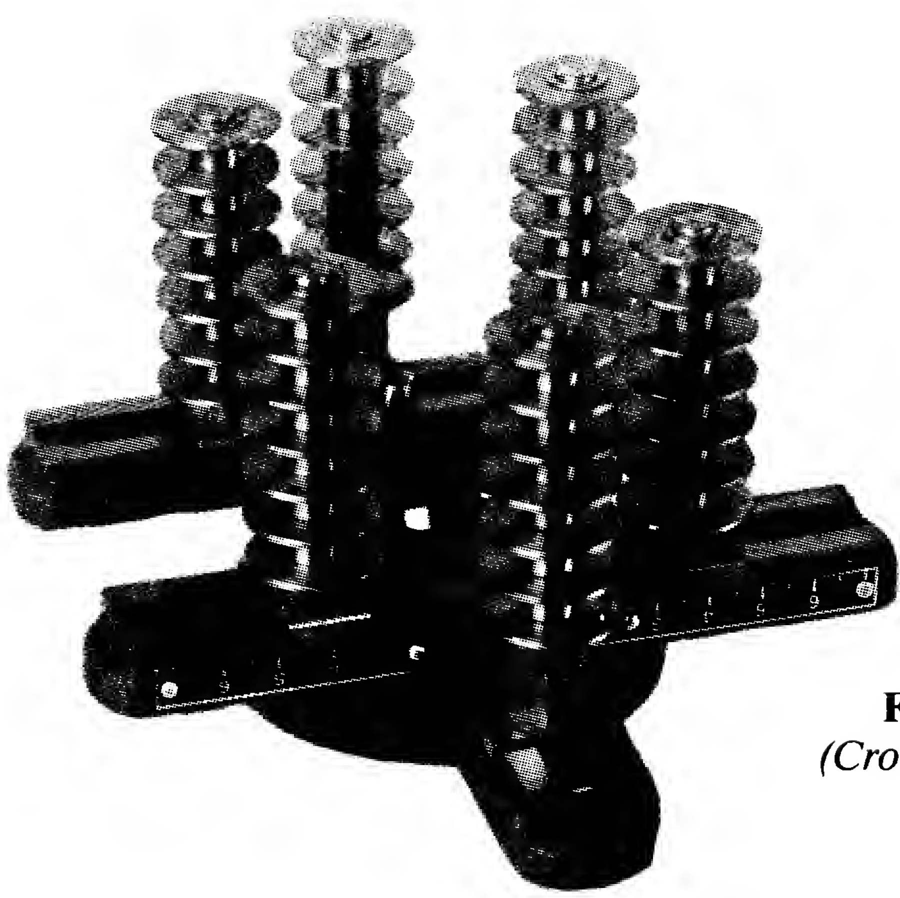
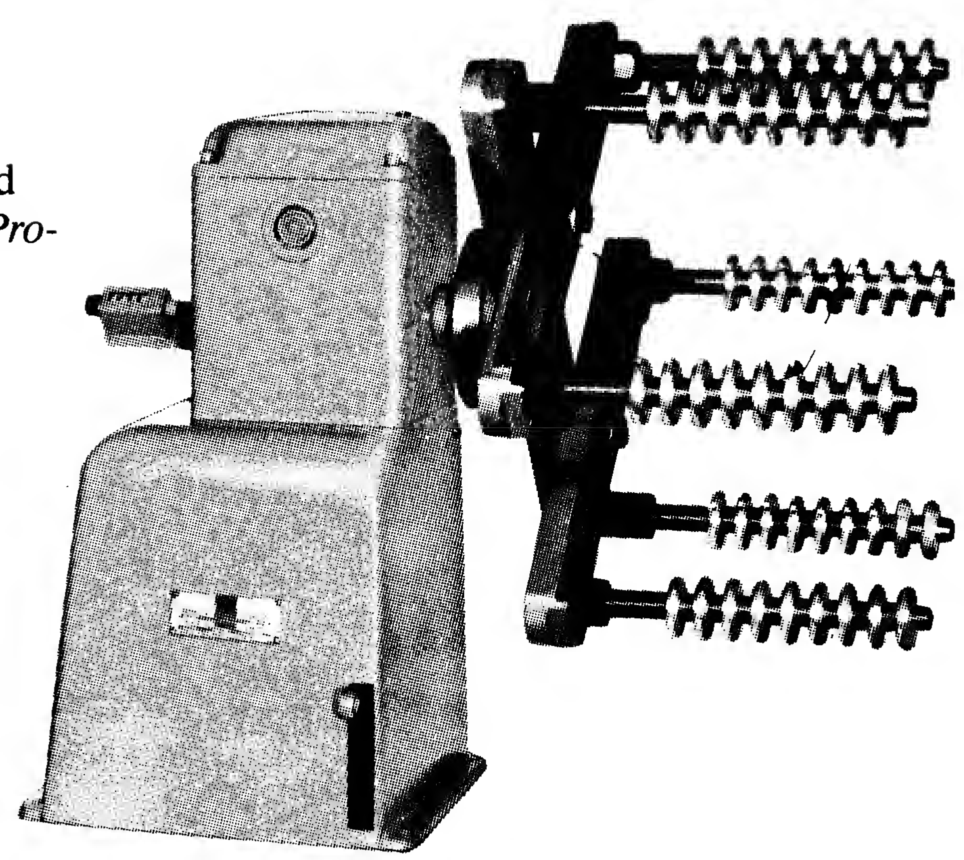


Fig. 3–26. Midget coil winding head. *(Crown Industrial Products Co.)*

Fig. 3–27. Coil winding drive and three-phase head. *(Crown Industrial Products Co.)*



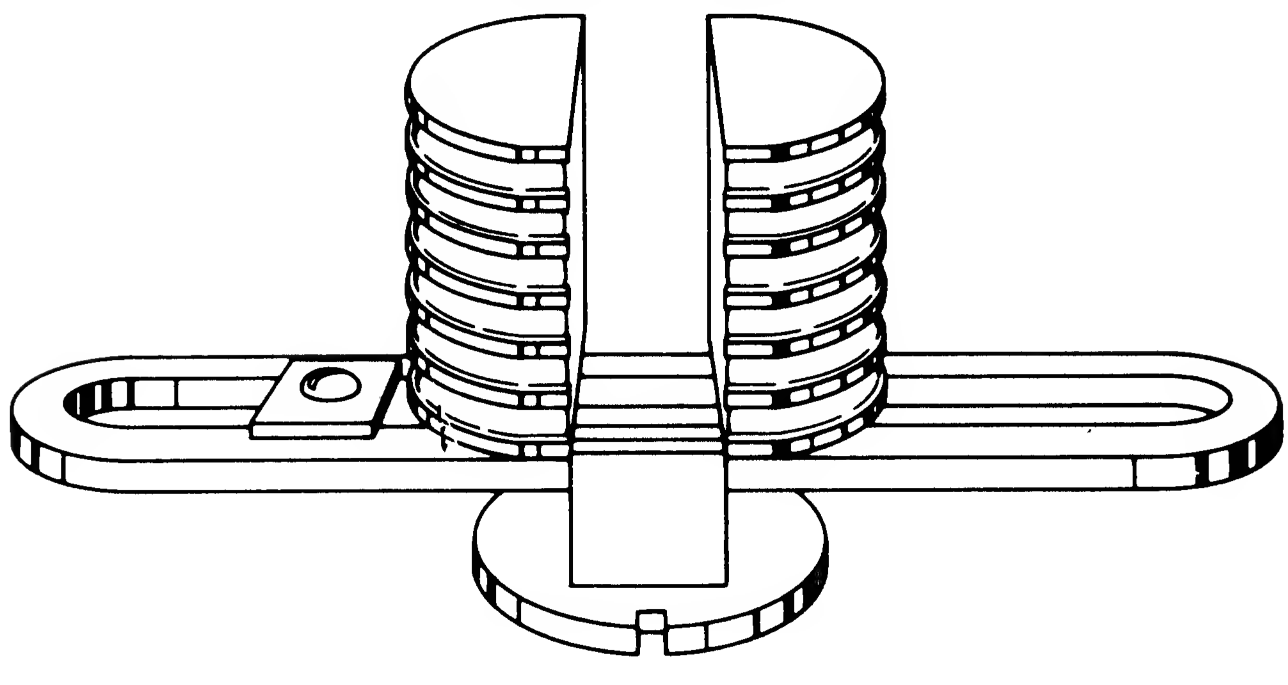


Fig. 3–28. Three-phase head for rounded coils.

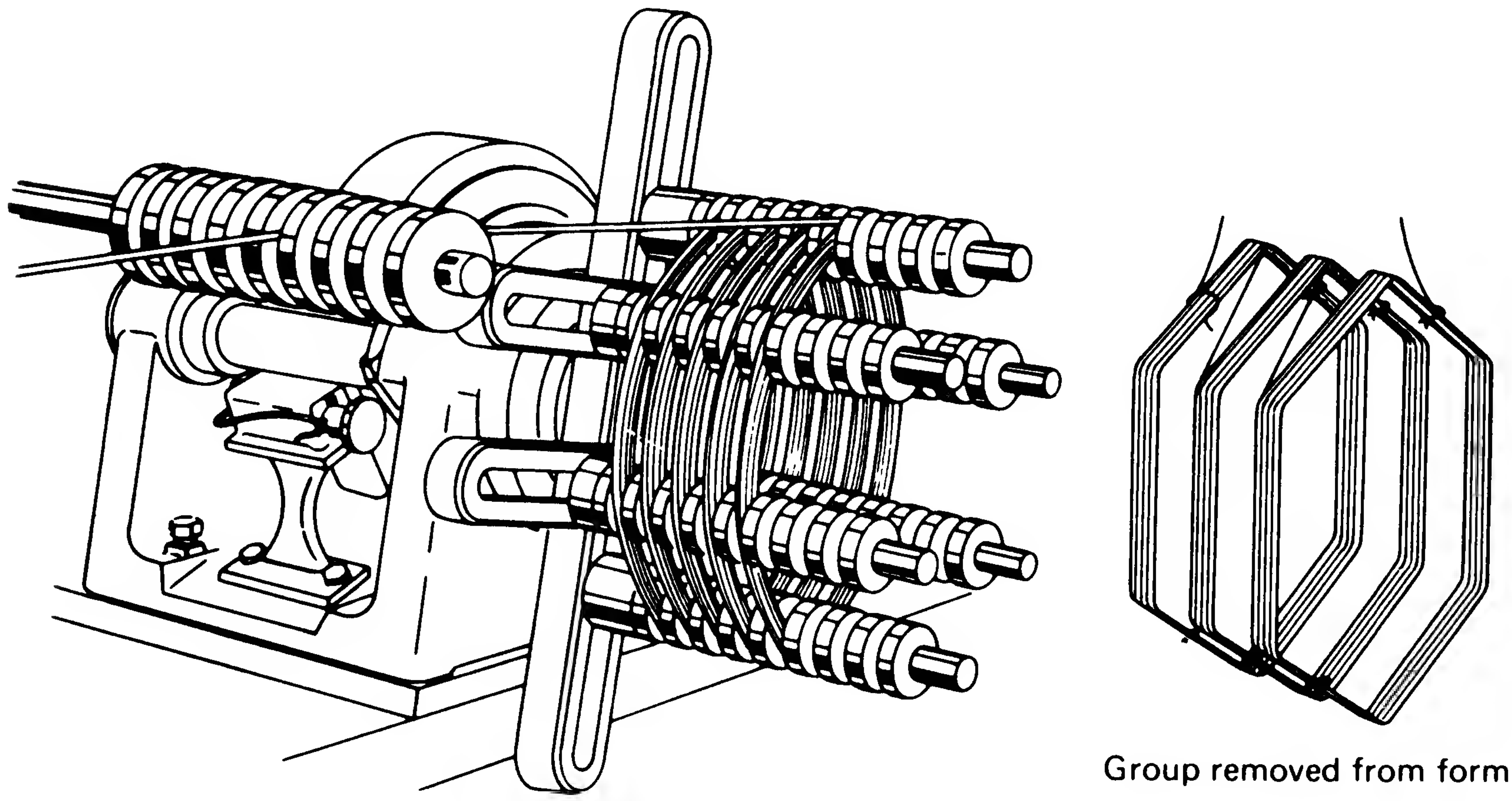


Fig. 3-29. Method of winding coils in groups.

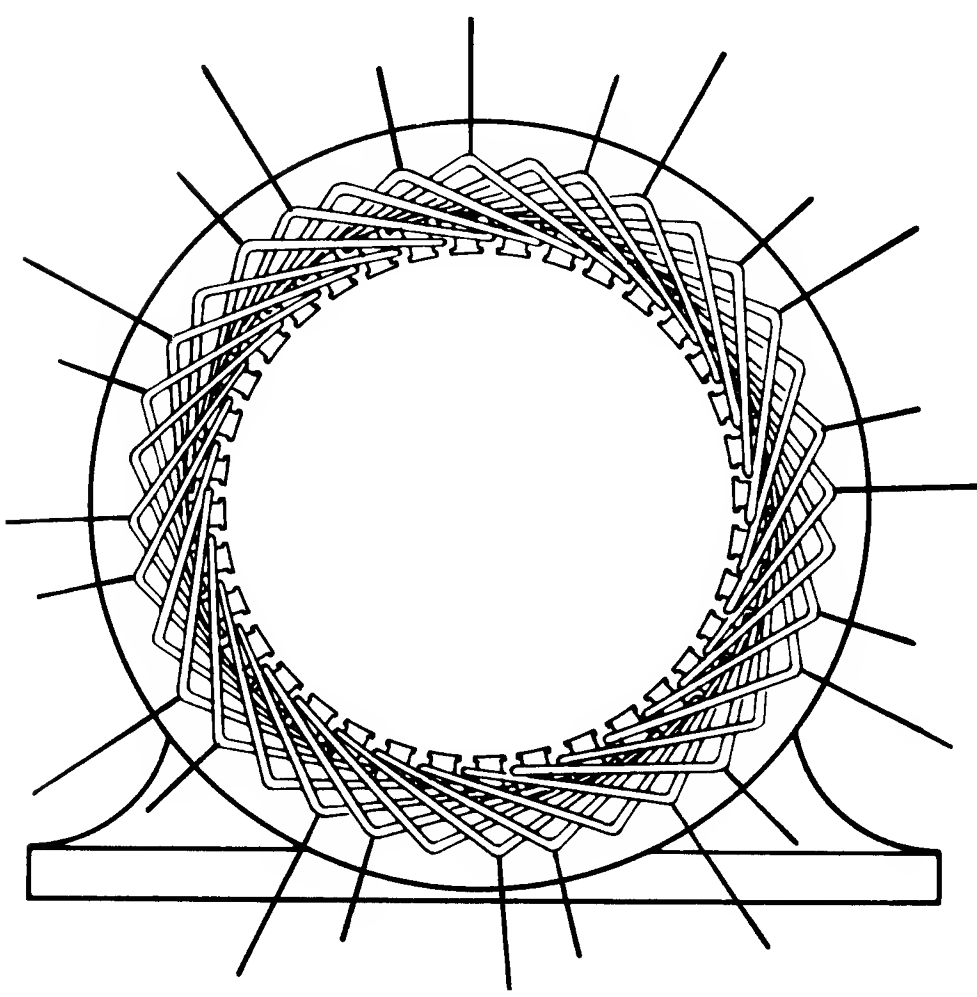


Fig. 3-30. A stator of a three-phase motor with all the coils in their slots.

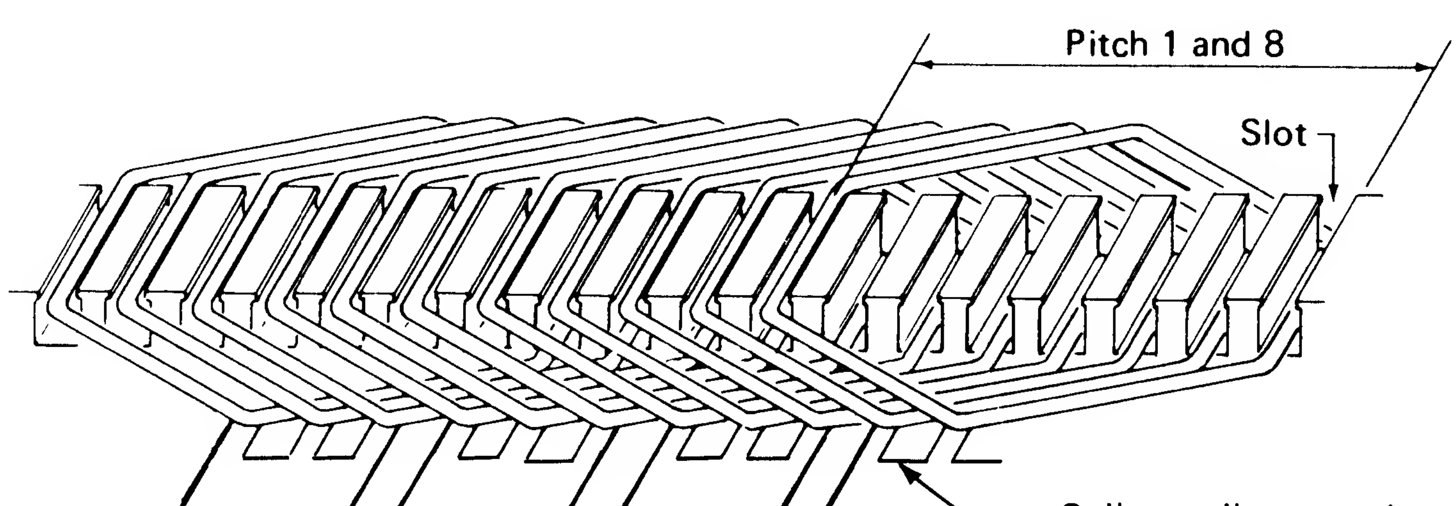


Fig. 3-31. A portion of a three-phase winding as it would appear if the slots were laid flat.

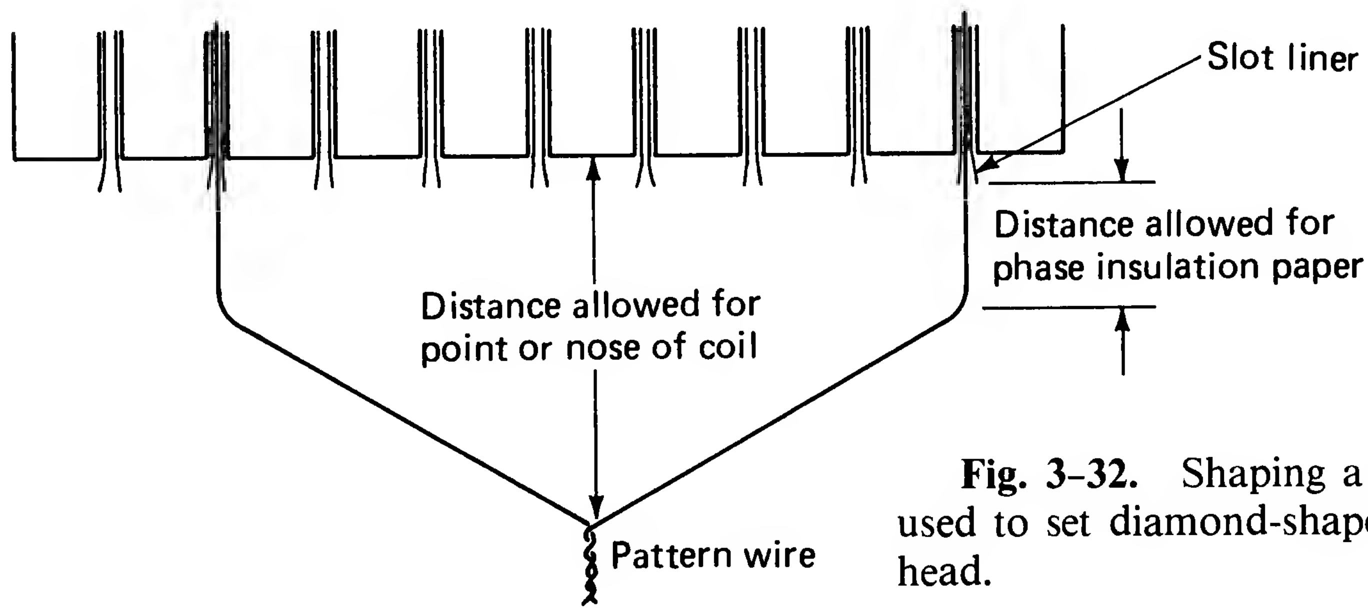


Fig. 3–32. Shaping a pattern wire used to set diamond-shaped winding head.

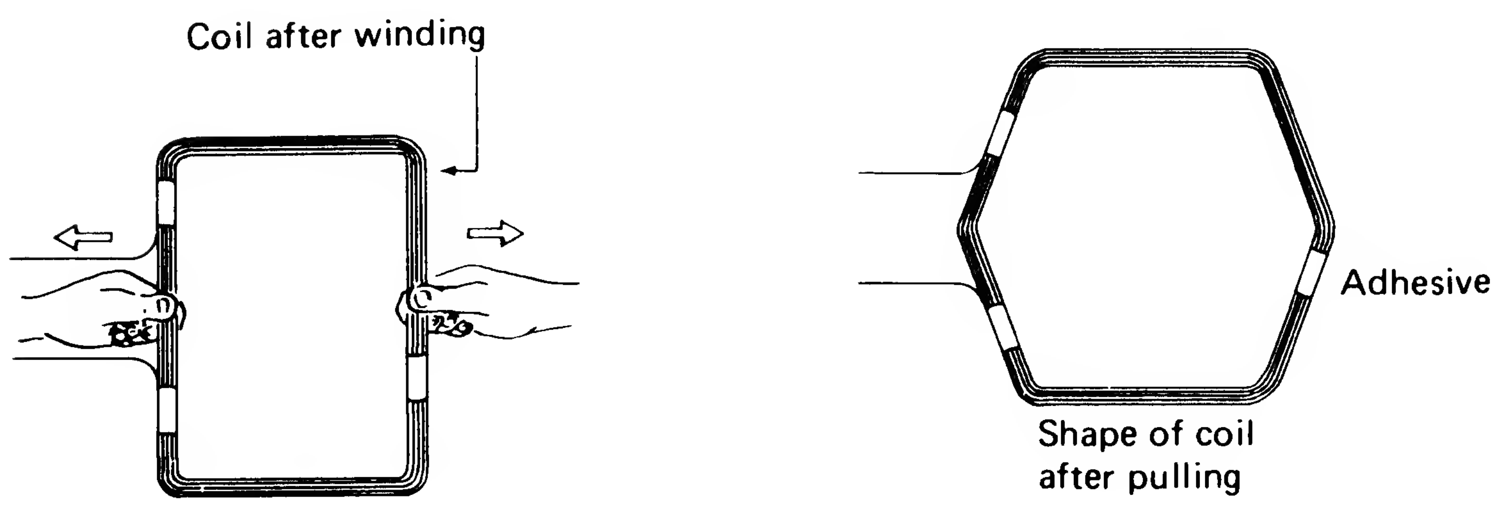


Fig. 3–33. The coils of small motors may be wound in a rectangular shape, which is later formed into a diamond shape by pulling at the center of opposite ends.

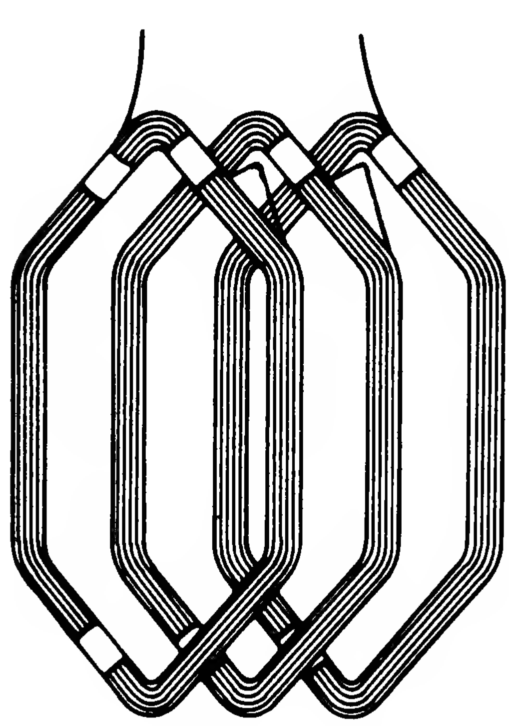


Fig. 3–34. This is a group-wound, three-coils-per-group coil group.

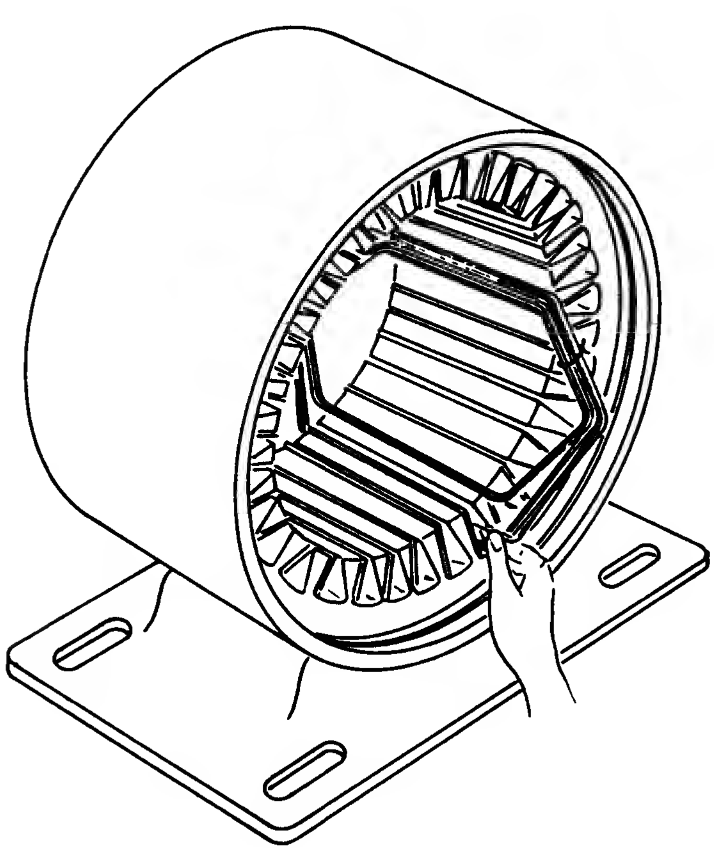


Fig. 3-35. One side of a coil spread so that it can be fed into the slot.

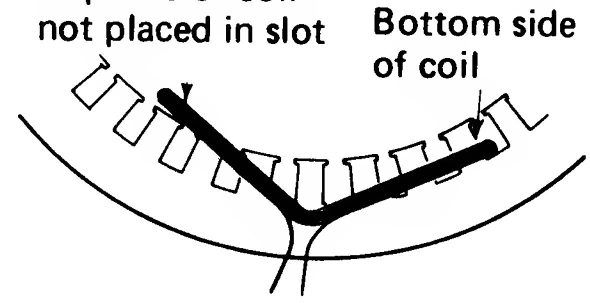


Fig. 3-36. Starting to place coils in slots.

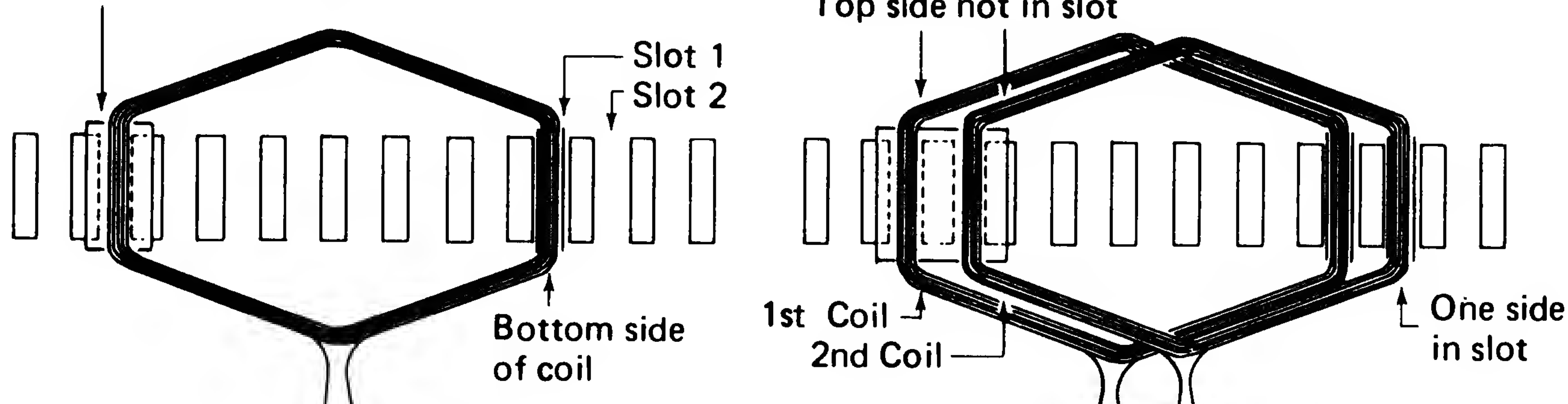


Fig. 3-37. The method of placing one side of each coil in slot.

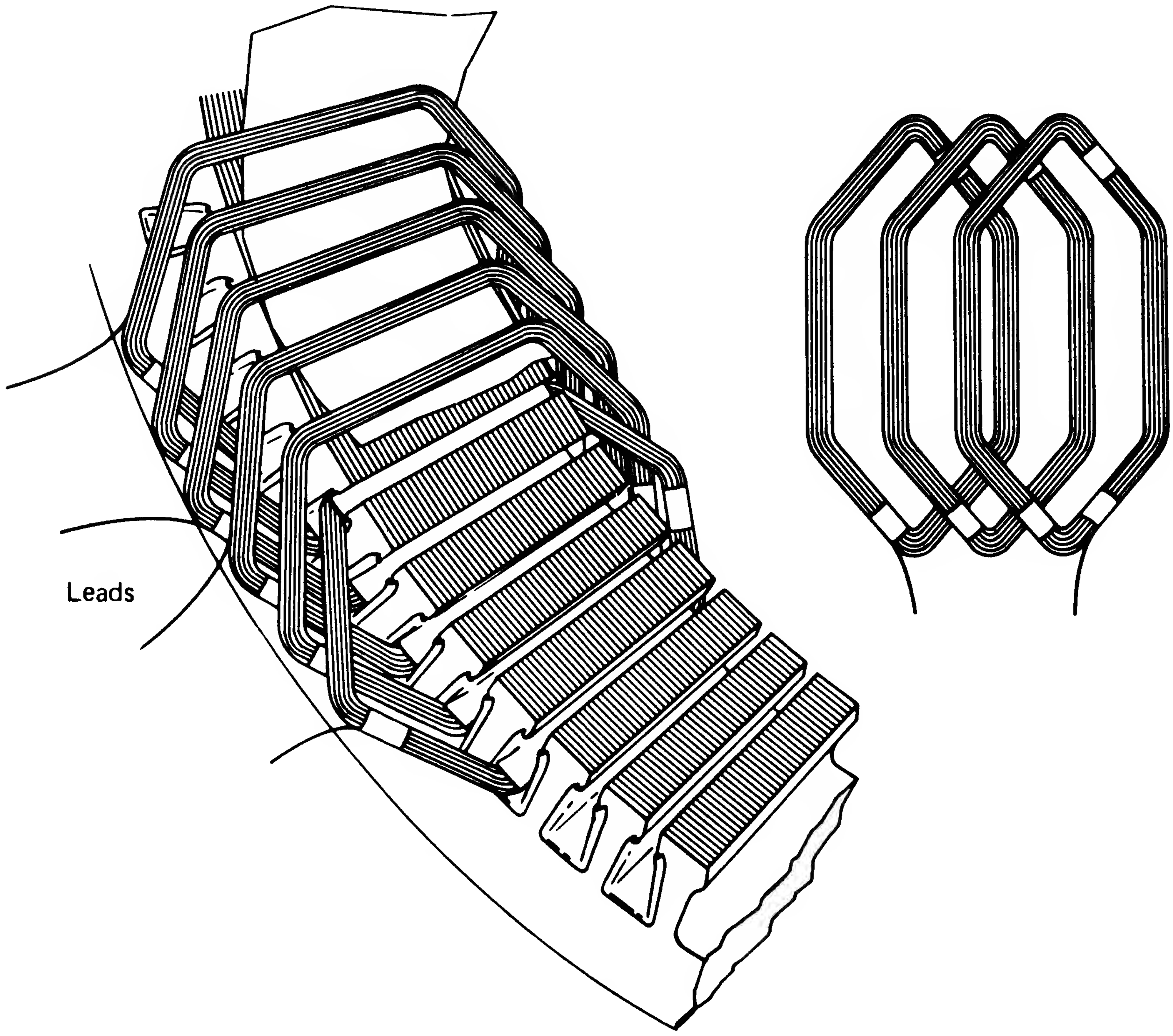


Fig. 3–38. Installing groups of 3 coils into the slots.

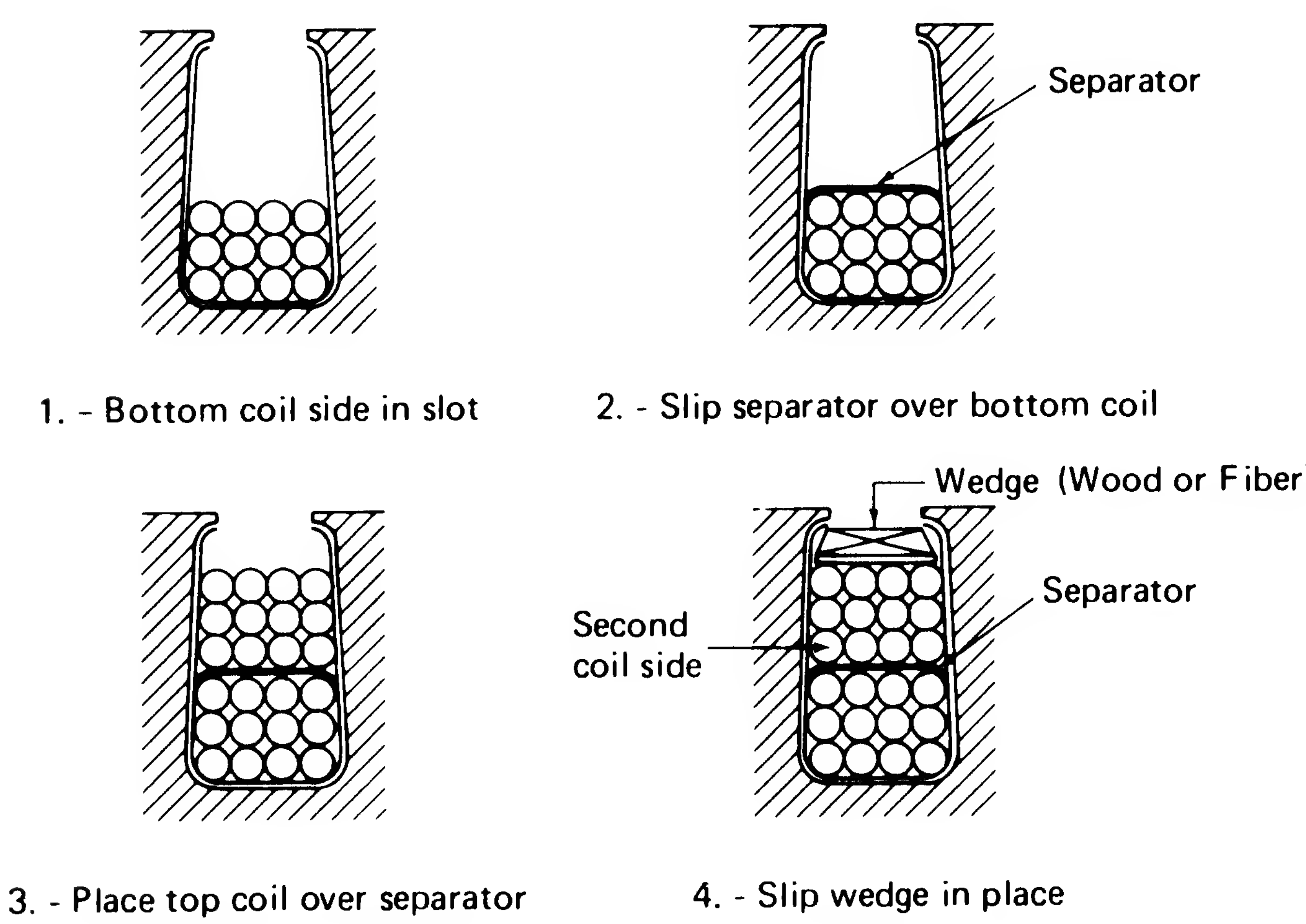


Fig. 3–39. The method of placing the sides of two coils in a slot with insulation.

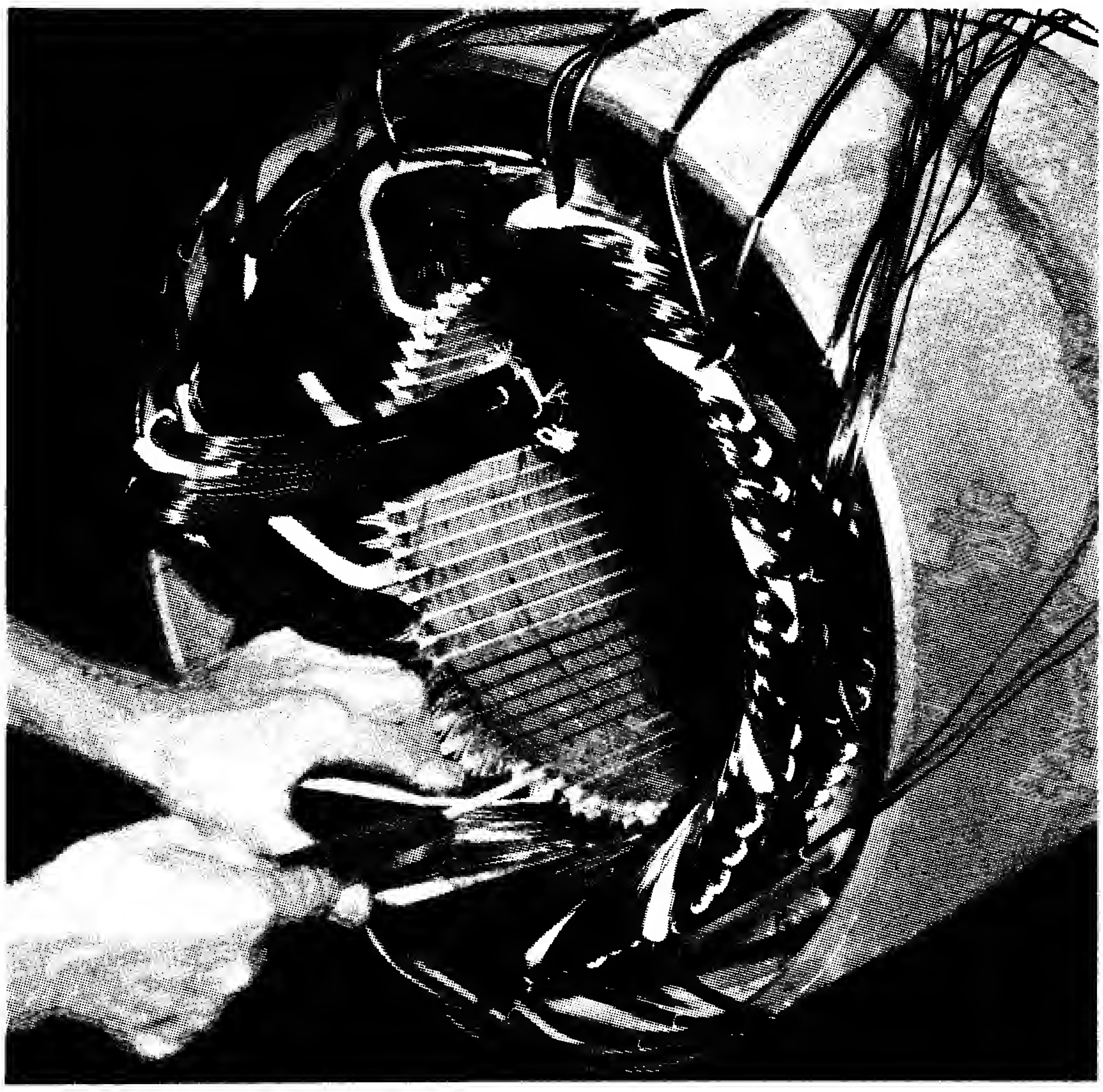


Fig. 3-40. Winding and insulating a three-phase stator. *(Wagner Electric Company)*

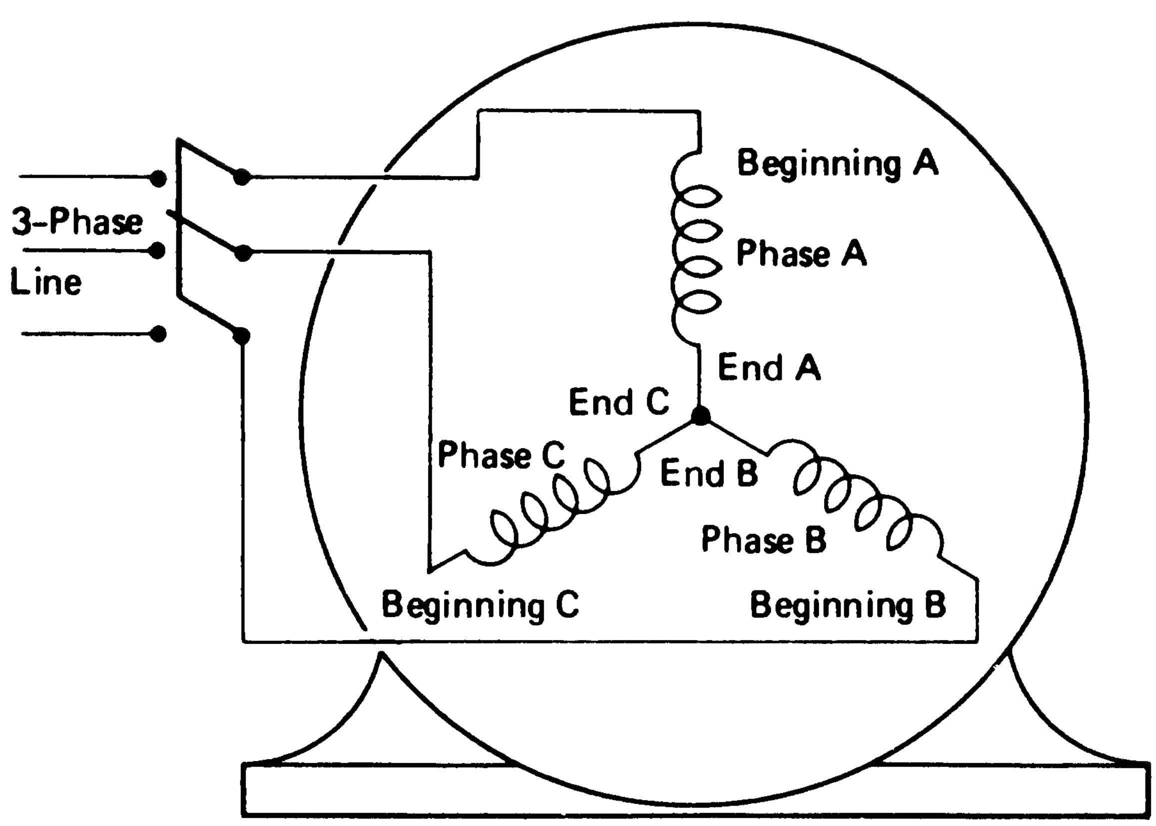


Fig. 3-41. A diagram of a star connection. This is also called a Y connection.

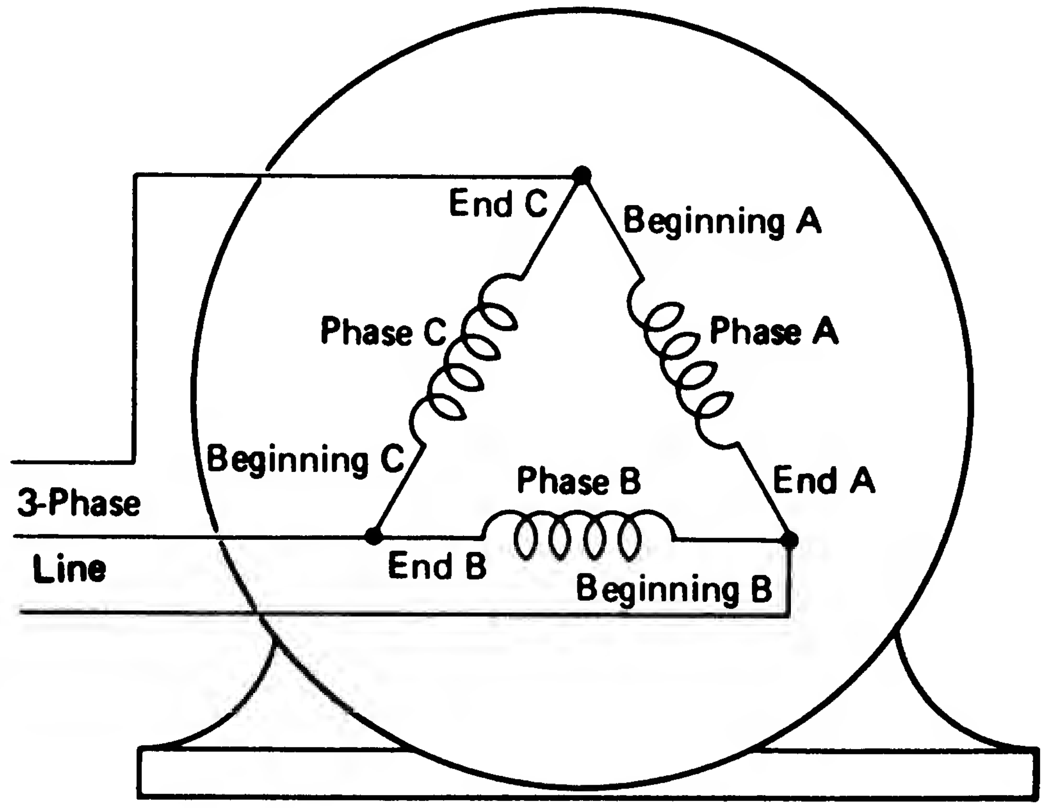


Fig. 3-42. A diagram of a delta connection.

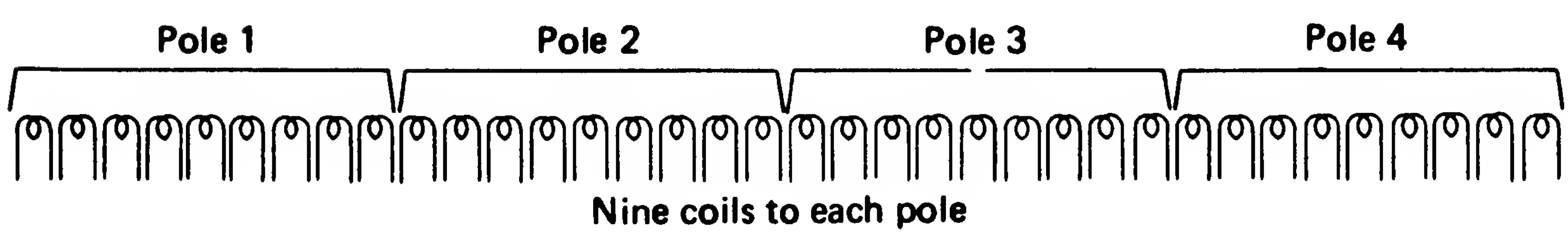


Fig. 3-43. A 36-coil, three-phase motor with coils divided into poles.

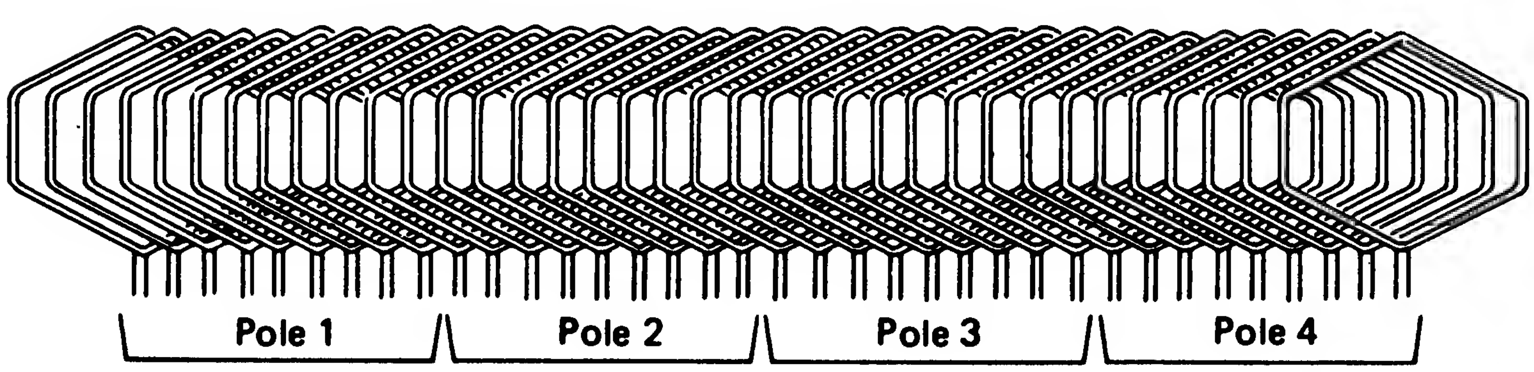


Fig. 3-44. The true shape of coils shown in Fig. 3-43.

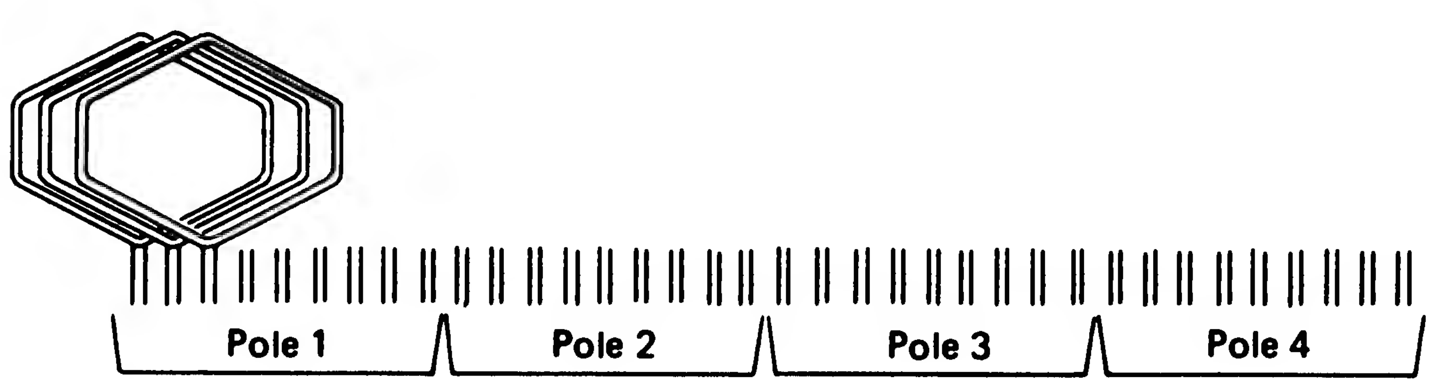


Fig. 3-45. A simplified diagram of the coils in a three-phase, four-pole motor.

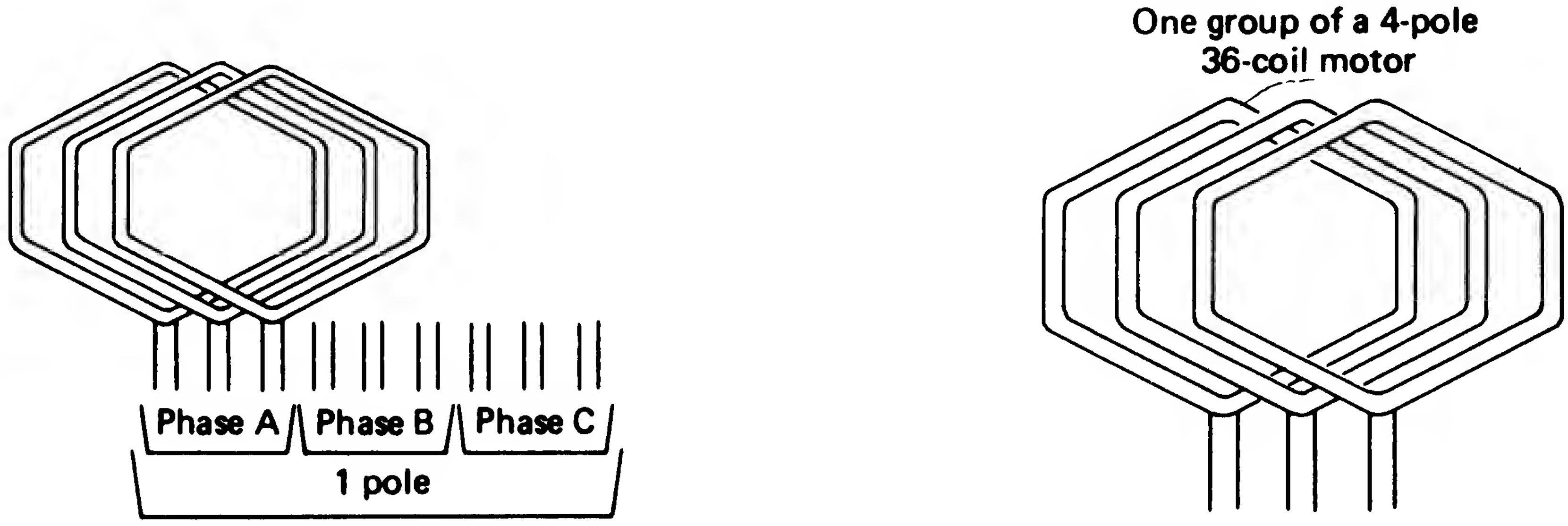
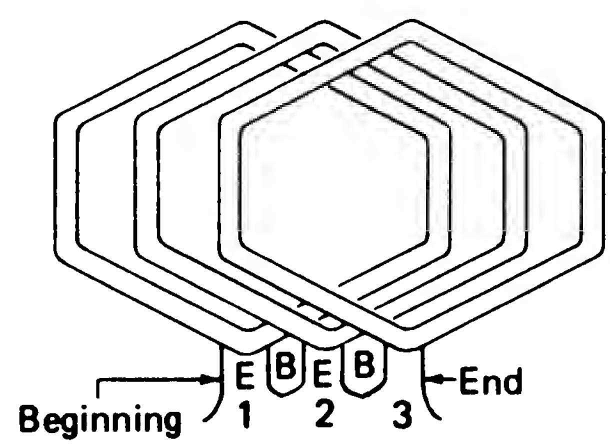


Fig. 3–46. Three groups in one pole. Each group has three coils.

Fig. 3–47. How the coils in a group are connected together.



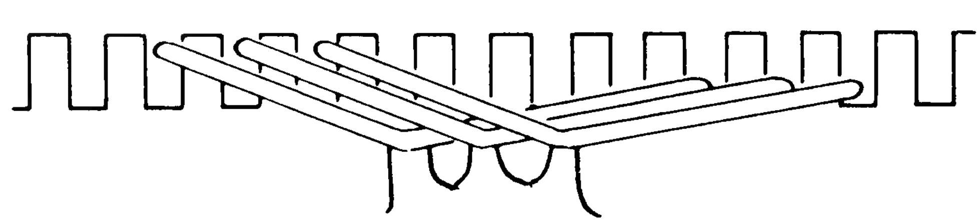


Fig. 3–48a. A side view of the coil connections shown in **Fig. 3–47.**

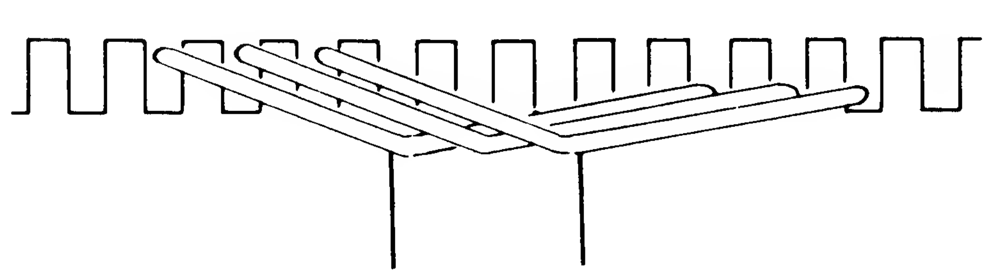


Fig. 3–48b. Three coils are group wound. Connections between coils are automatically made during the winding process.

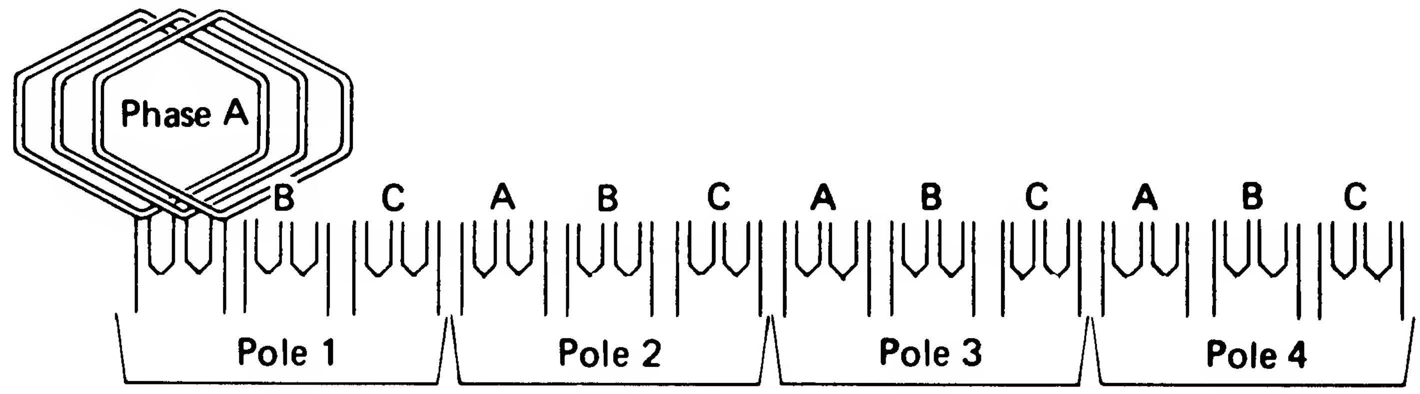


Fig. 3-49. Coils connected in twelve groups of three coils each. Note that all poles are alike.

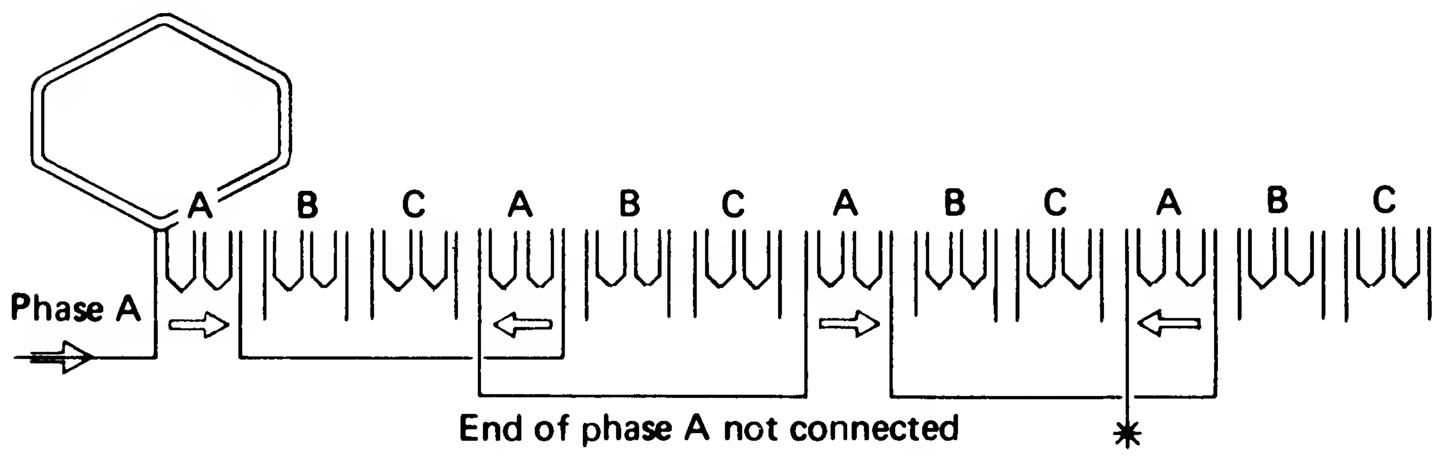


Fig. 3-50. Connections of groups of phase *A*.

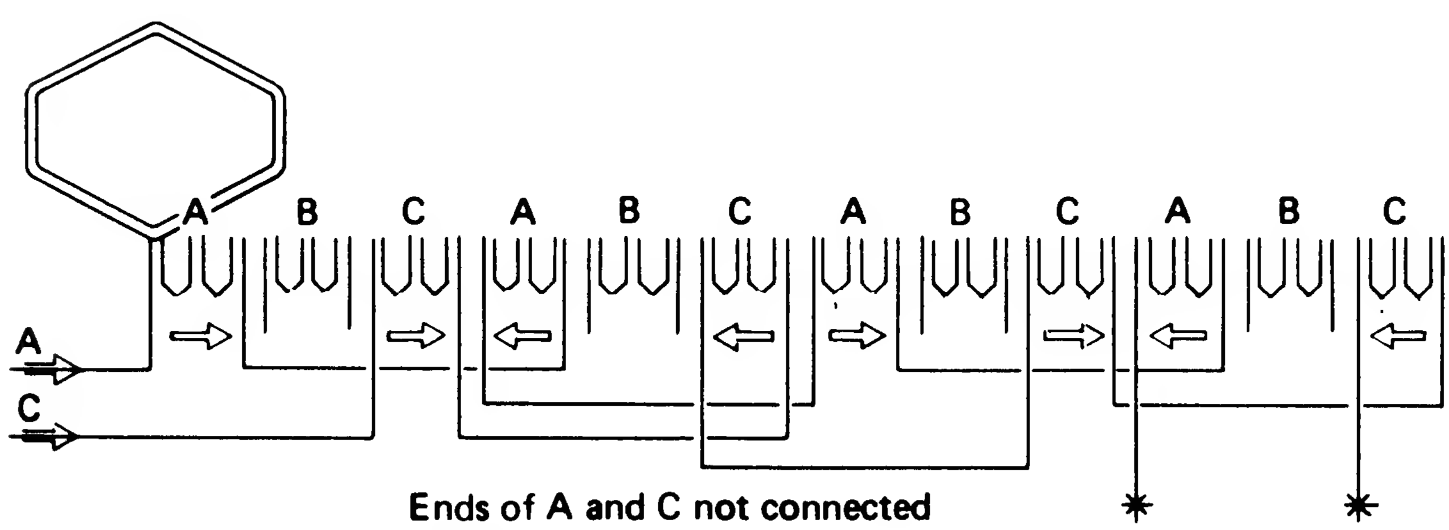


Fig. 3-51. Phase *C* connected exactly like phase *A* and connected before phase *B* to simplify connections.

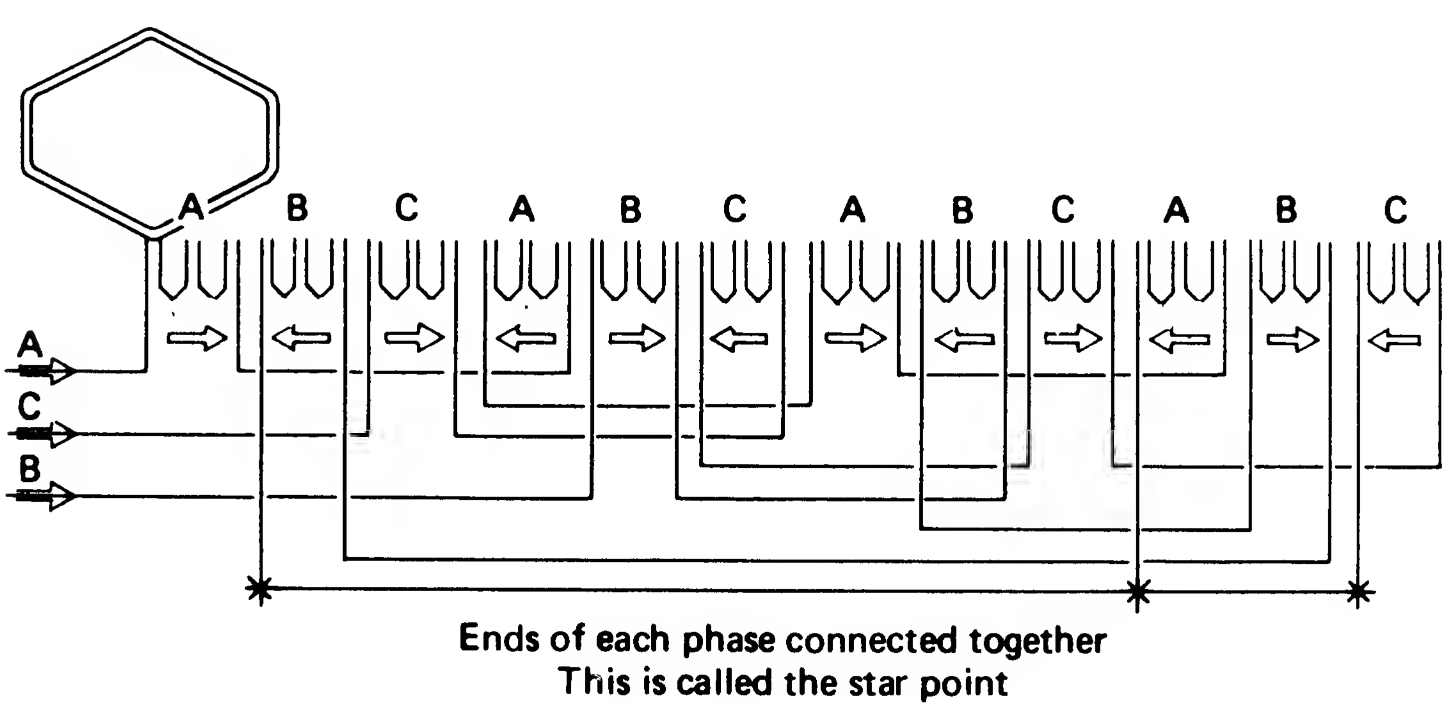


Fig. 3-52. The current flow in the *B* phase is opposite to the current flow in both the *A* and *C* phases. This is shown by the arrows under each group.

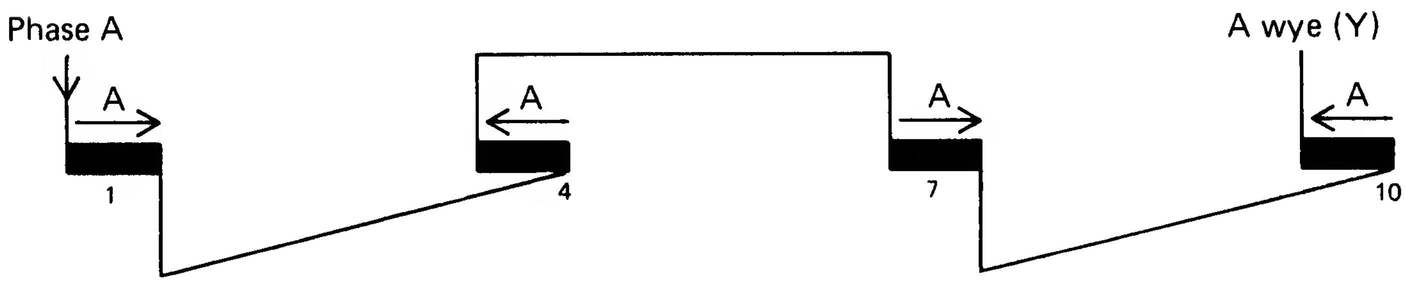


Fig. 3–53a. Connections of groups of phase *A*.

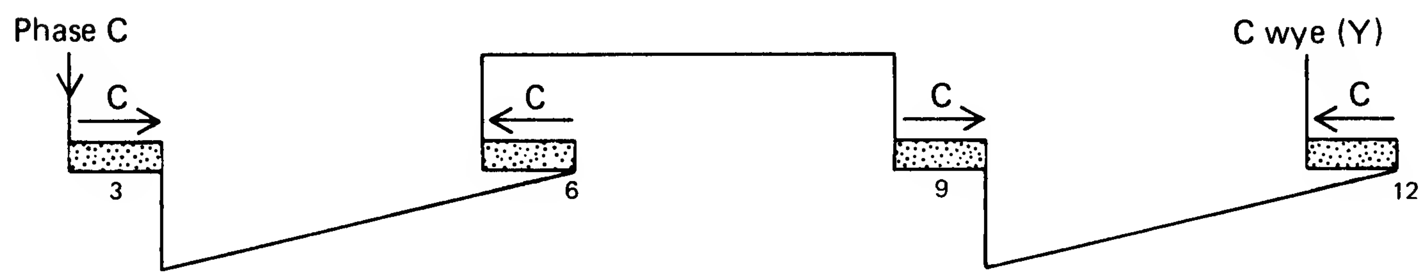


Fig. 3–53b. Phase *C* connected exactly like phase *A* and connected before phase *B* to simplify connections.

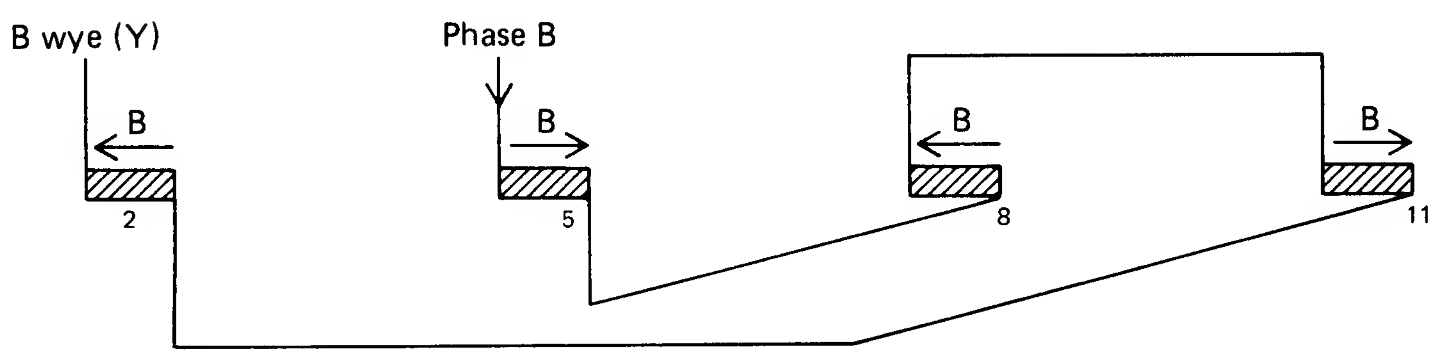


Fig. 3–53c. The current flow in the *B* phase is the opposite to the current flow in both the *A* and *C* phases. This is accomplished by starting the *B* phase at the fifth group or the second *B*-phase group.

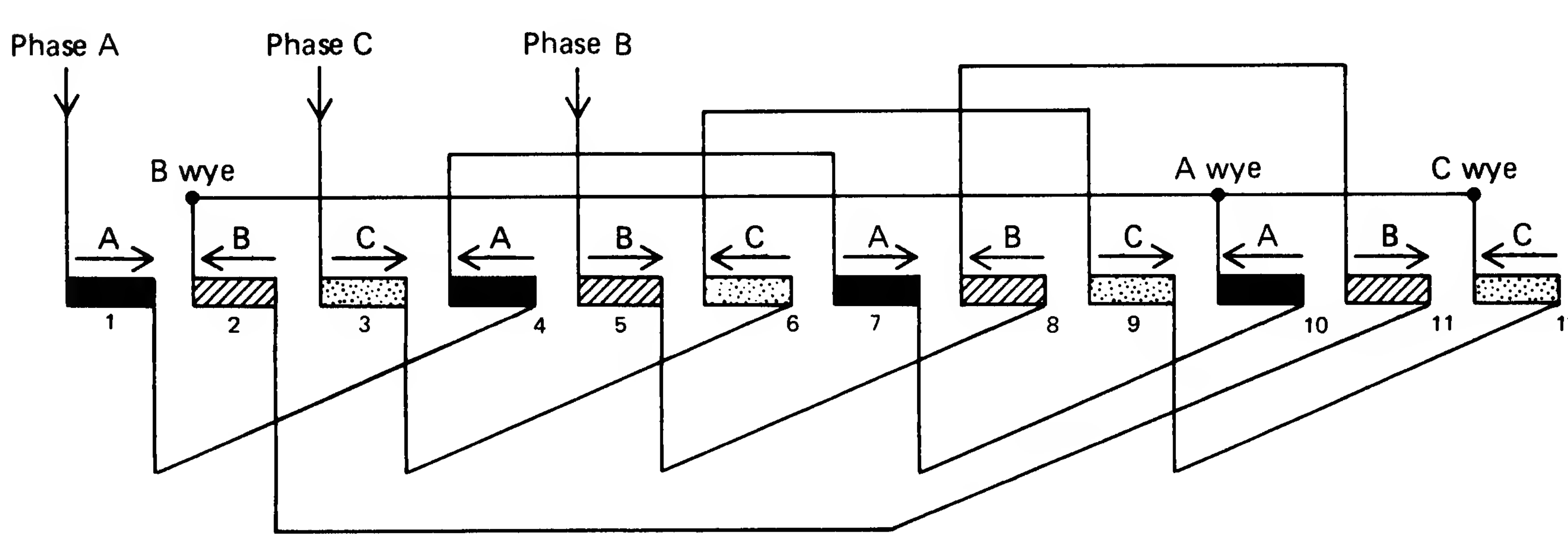


Fig. 3–53d. A complete diagram of a three-phase, four-pole, one-wye (1Y) or series-wye-connected motor.

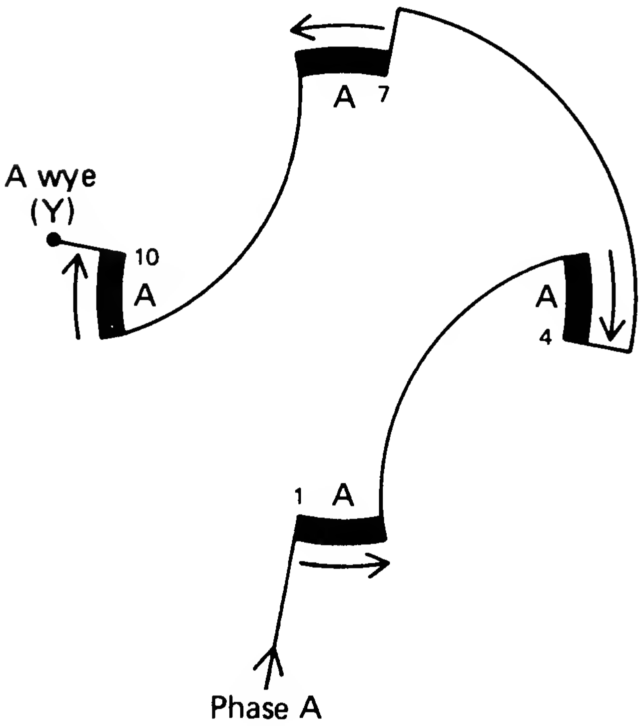


Fig. 3–54a. A circular diagram showing the *A* phase only.

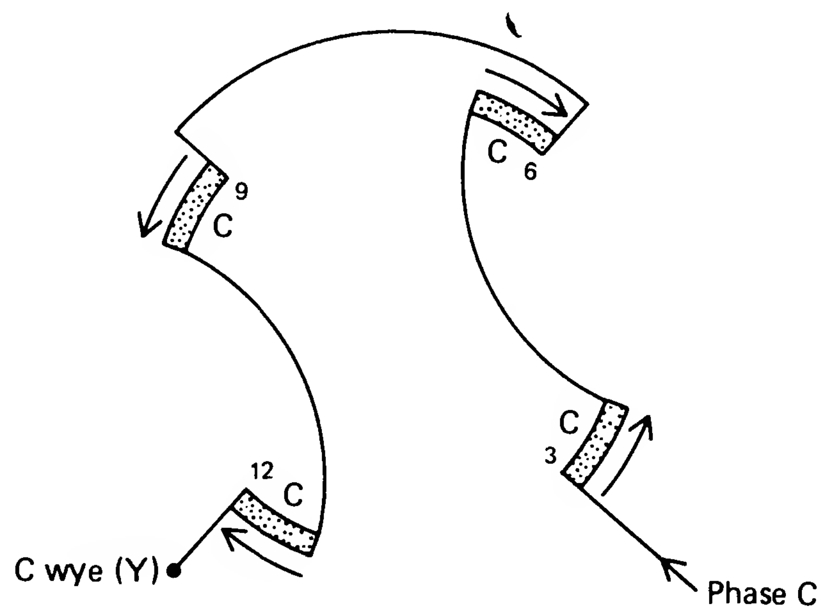


Fig. 3–54b. Phase *C* connected exactly like phase *A* before phase *B* to simplify connections.

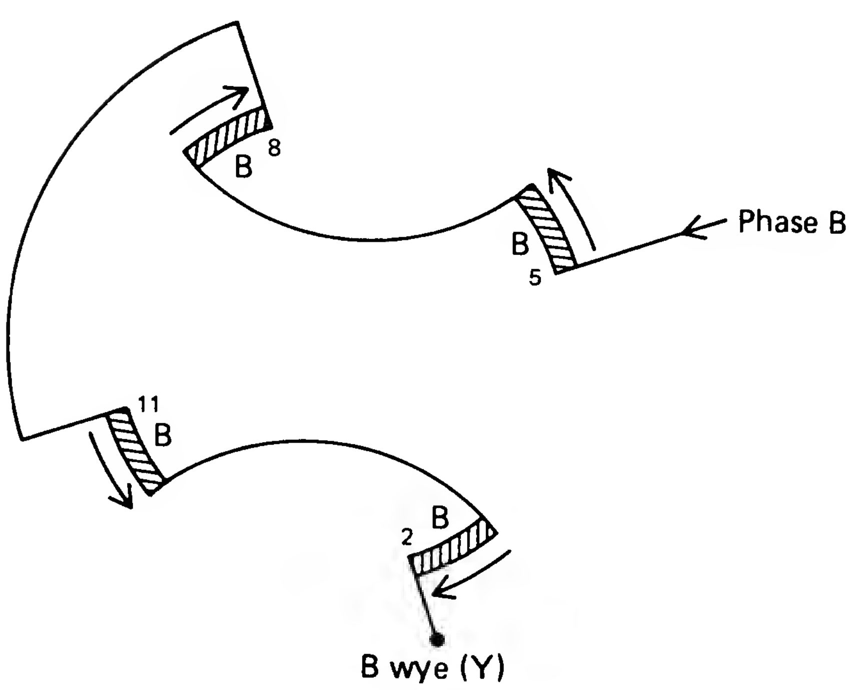


Fig. 3–54c. The current flow in the *B* phase is the opposite to the current flow in both the *A* and *C* phases. This is accomplished by starting the *B* phase at the fifth group or the second *B* phase group.

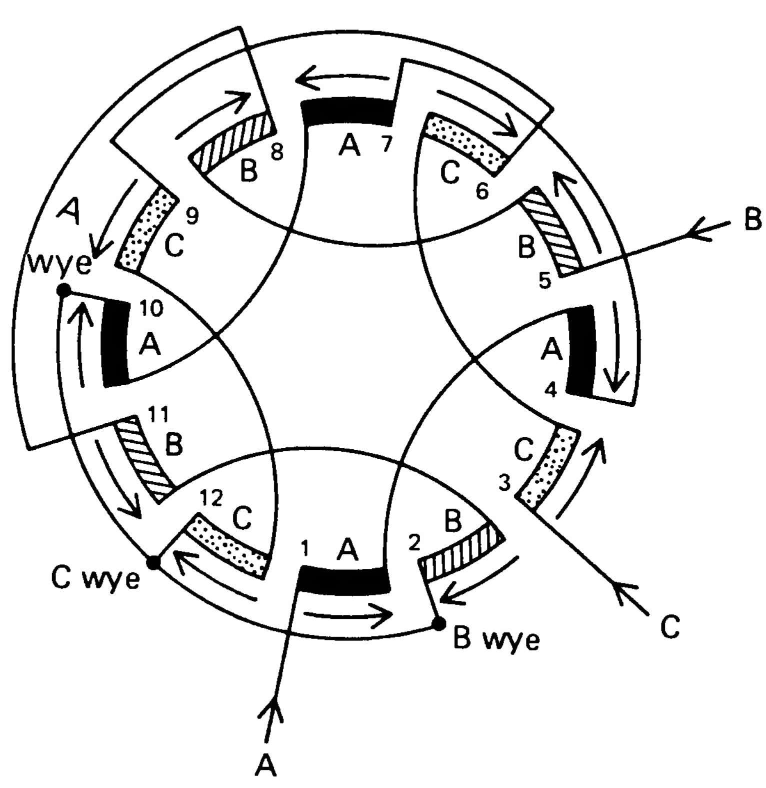


Fig. 3–54d. A circular diagram putting all three phases together. A one-wye short jumper with connections starting at the 6 o'clock position and the groups numbers 1 through 12.

Figures 3–54a; 3–54b; 3–54c; 3–54d

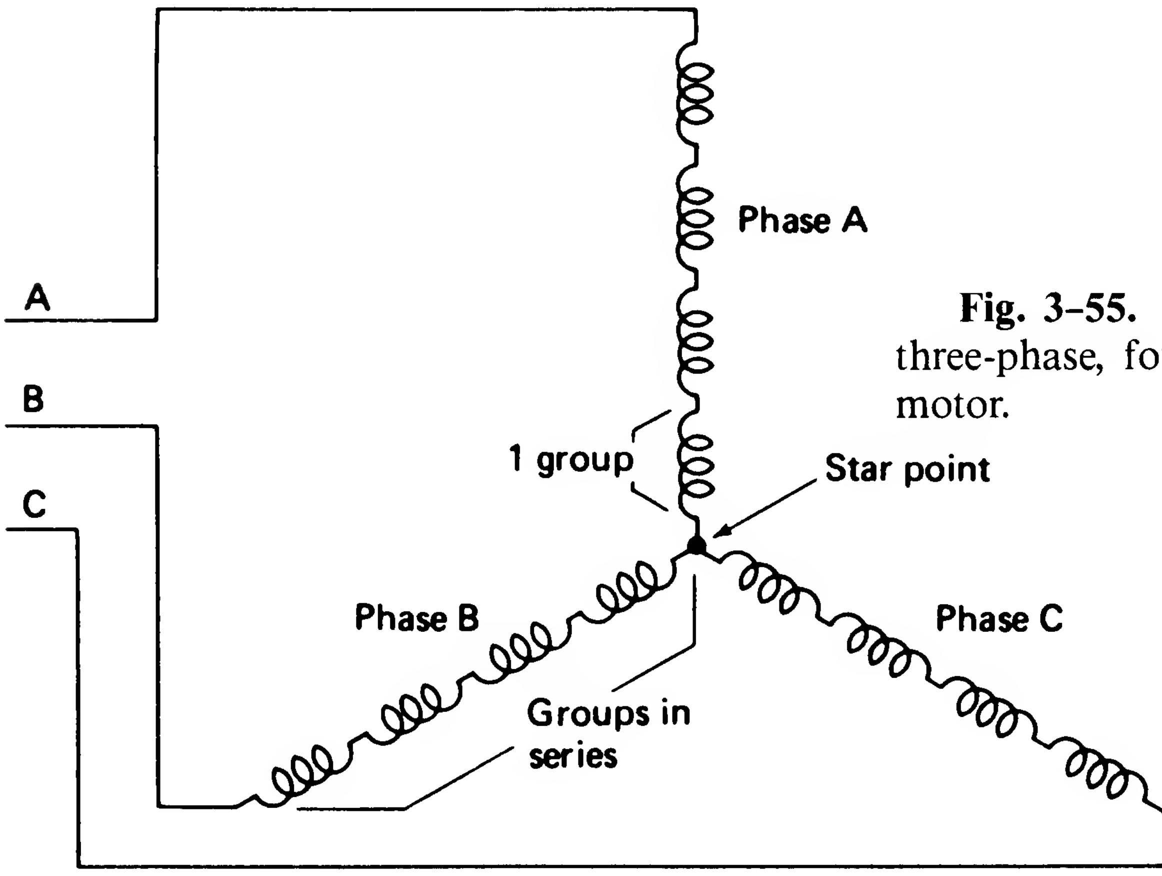


Fig. 3-55. A schematic diagram of a three-phase, four-pole, series star (1Y) motor.

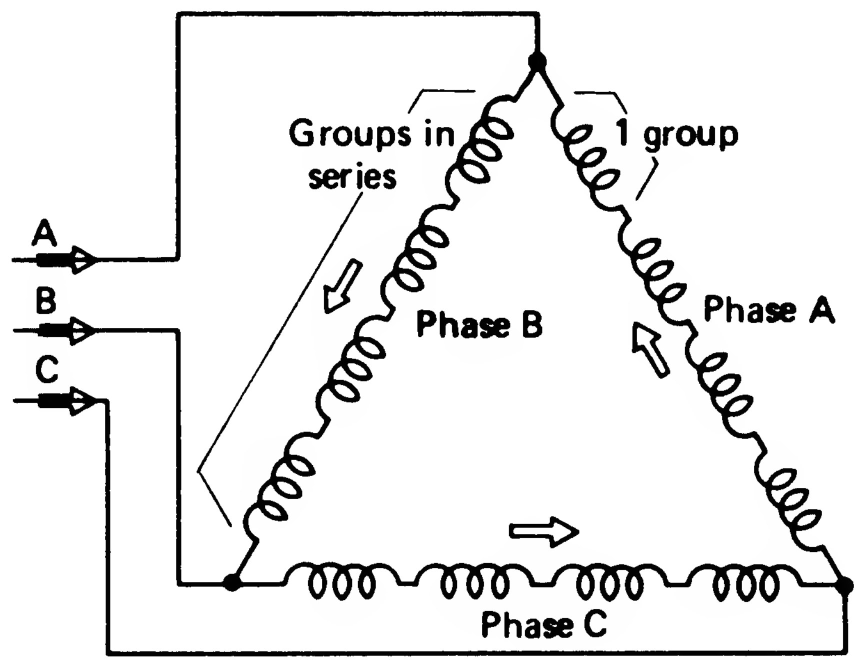


Fig. 3-56. A schematic diagram of a three-phase, four-pole, series delta motor.

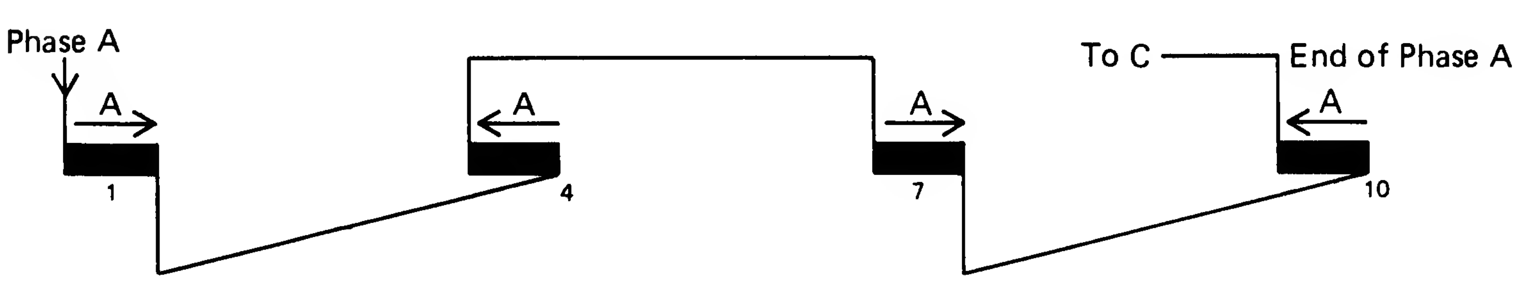


Fig. 3-57a. The *A* Phase connections for a one-delta, four-pole motor.

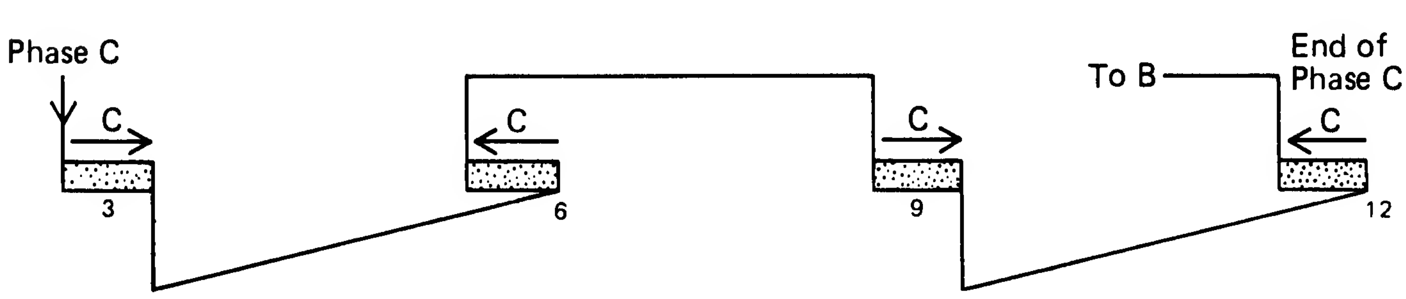


Fig. 3-57b. *C* Phase connections are the same as for the *A* phase.

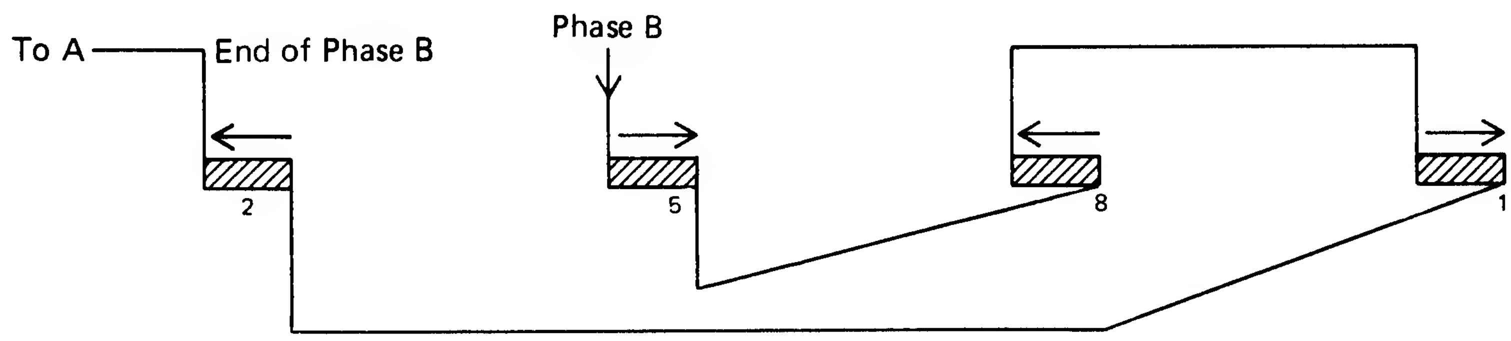


Fig. 3–57c. The *B* phase connected with polarity the opposite of the *A* and *C* phases.

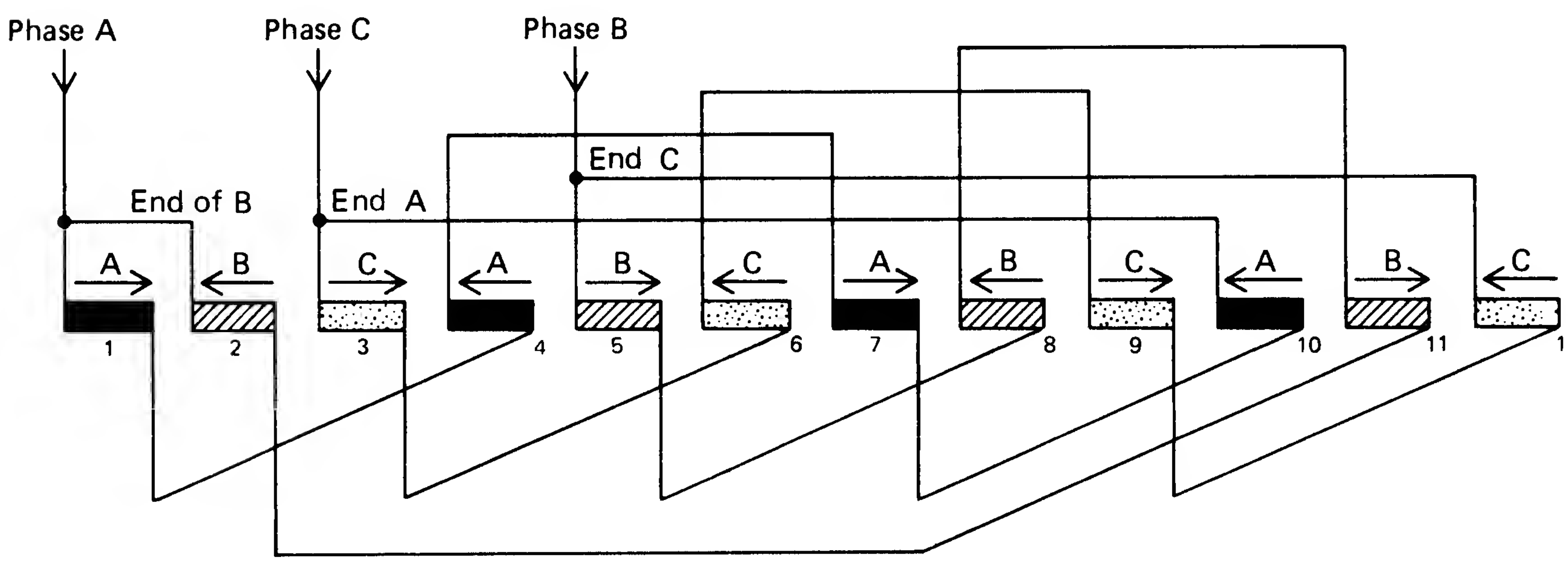


Fig. 3–57d. A complete diagram of a three-phase, one-delta, four-pole, short jumper motor.

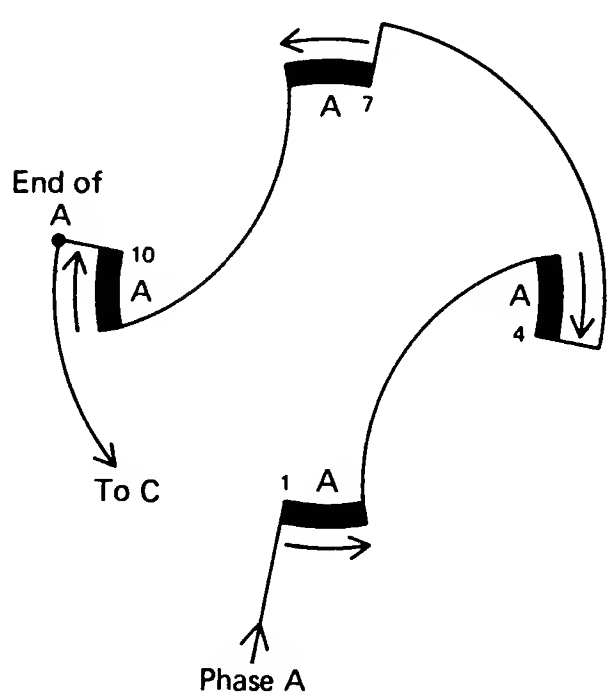


Fig. 3–58a. The connections of the *A* phase in a circular diagram.

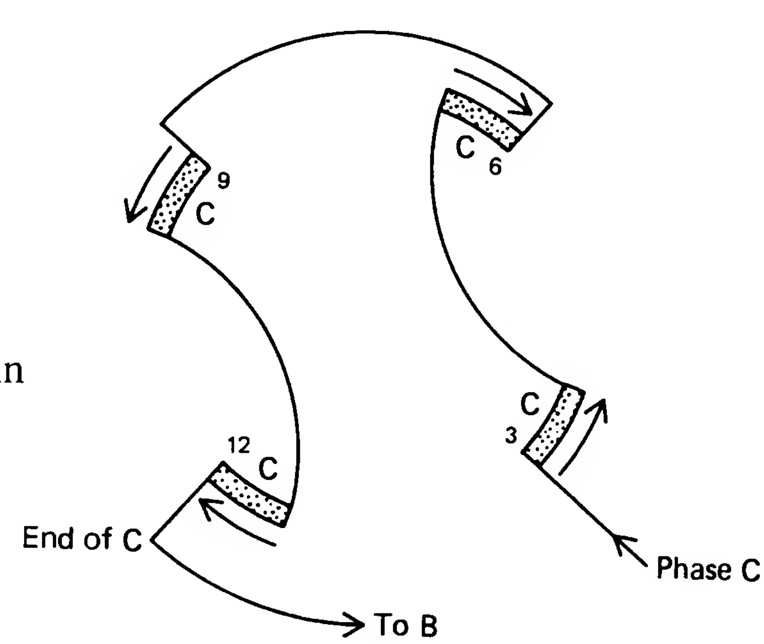


Fig. 3–58b. Phase *C* connected in the same way as for the *A* phase.

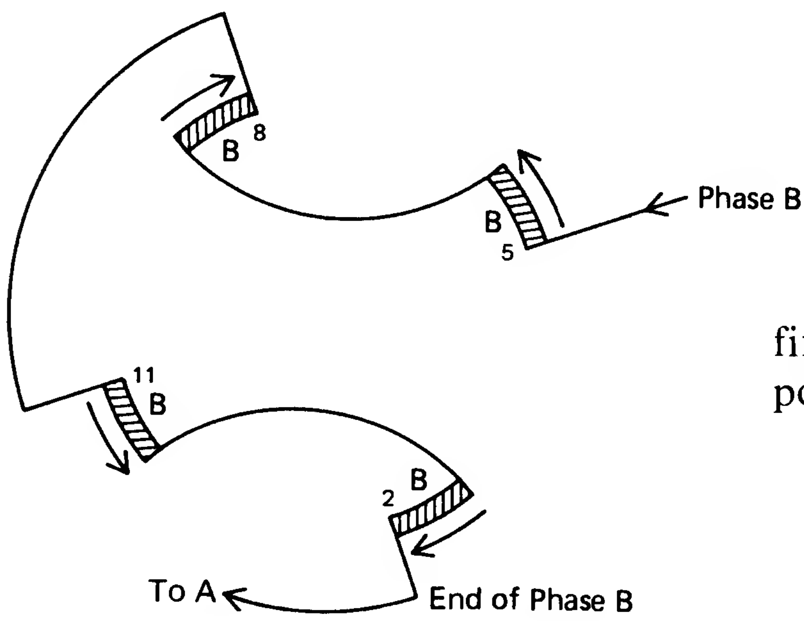


Fig. 3–58c. Phase *B* starting at the fifth group, thereby reversing the *B* phase polarity.

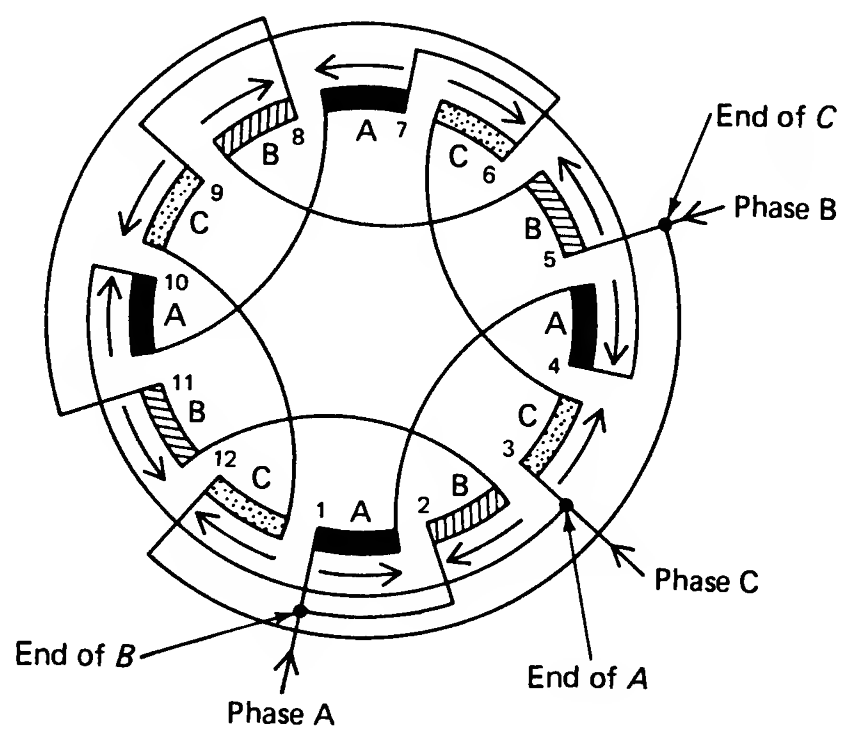


Fig. 3–58d. A circular diagram of a one-delta (series-delta), four-pole, short jumper connection.

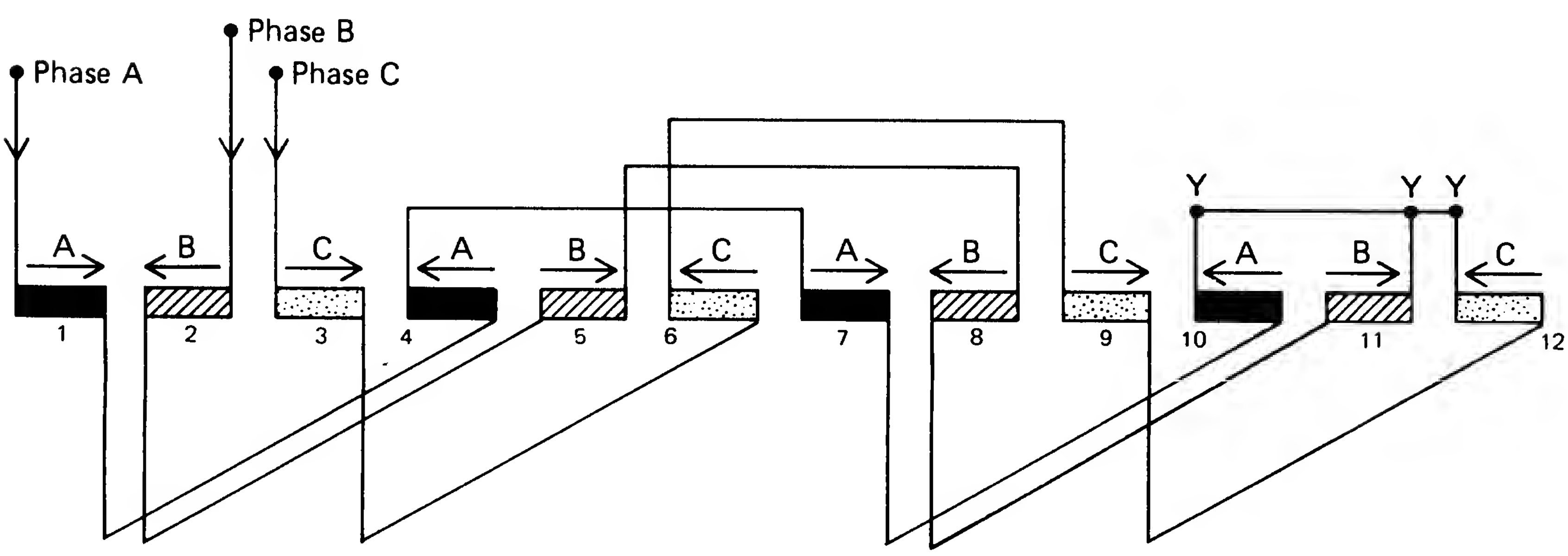


Fig. 3–59. A three-phase, series-wye connection in which the first phase *B* coil group is not skipped. Phase *A* and phase *C* are connected in the same way as when the skip group method is used.

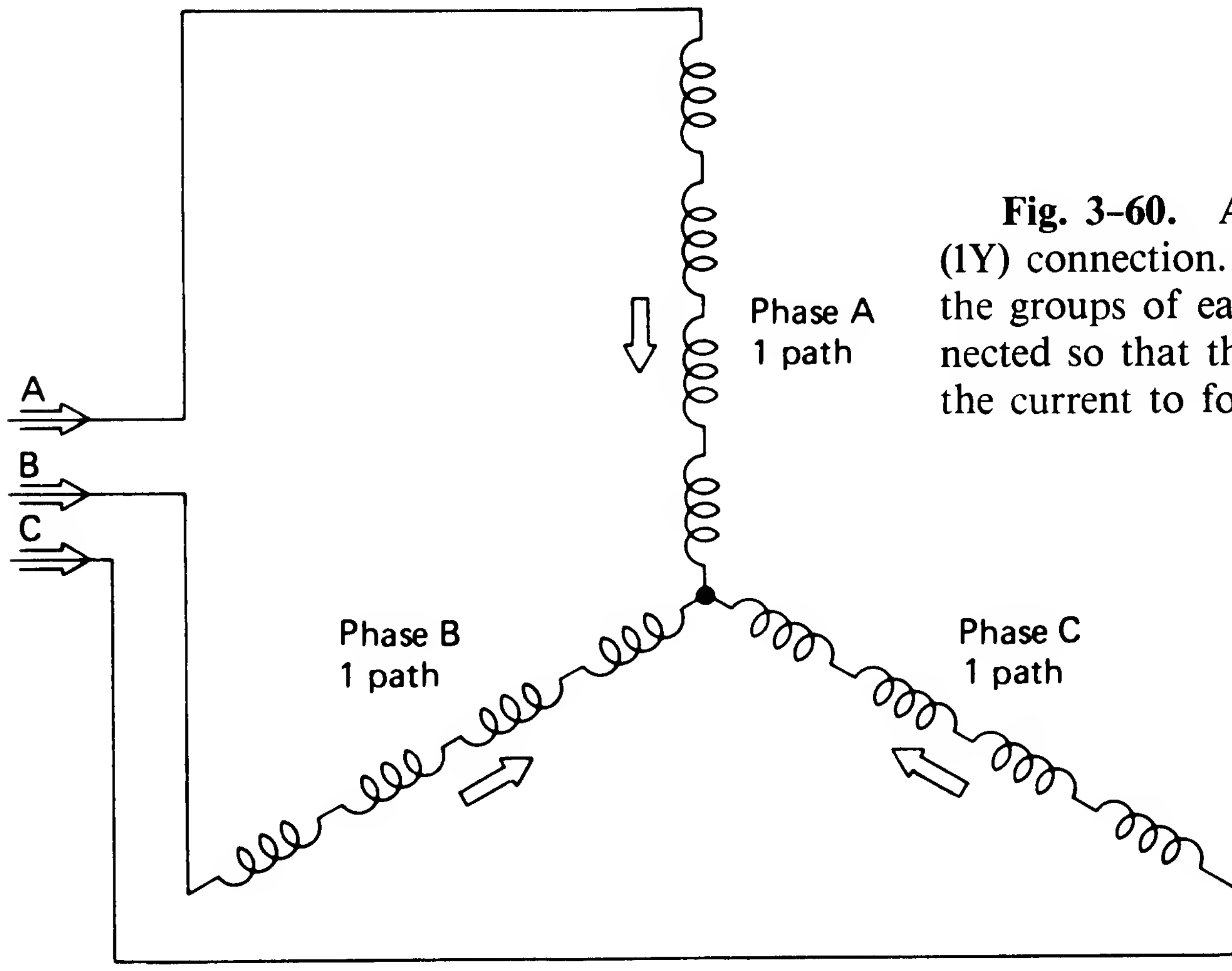


Fig. 3-60. A four-pole, series (1Y) connection. In this connection the groups of each phase are connected so that there is one path for the current to follow.

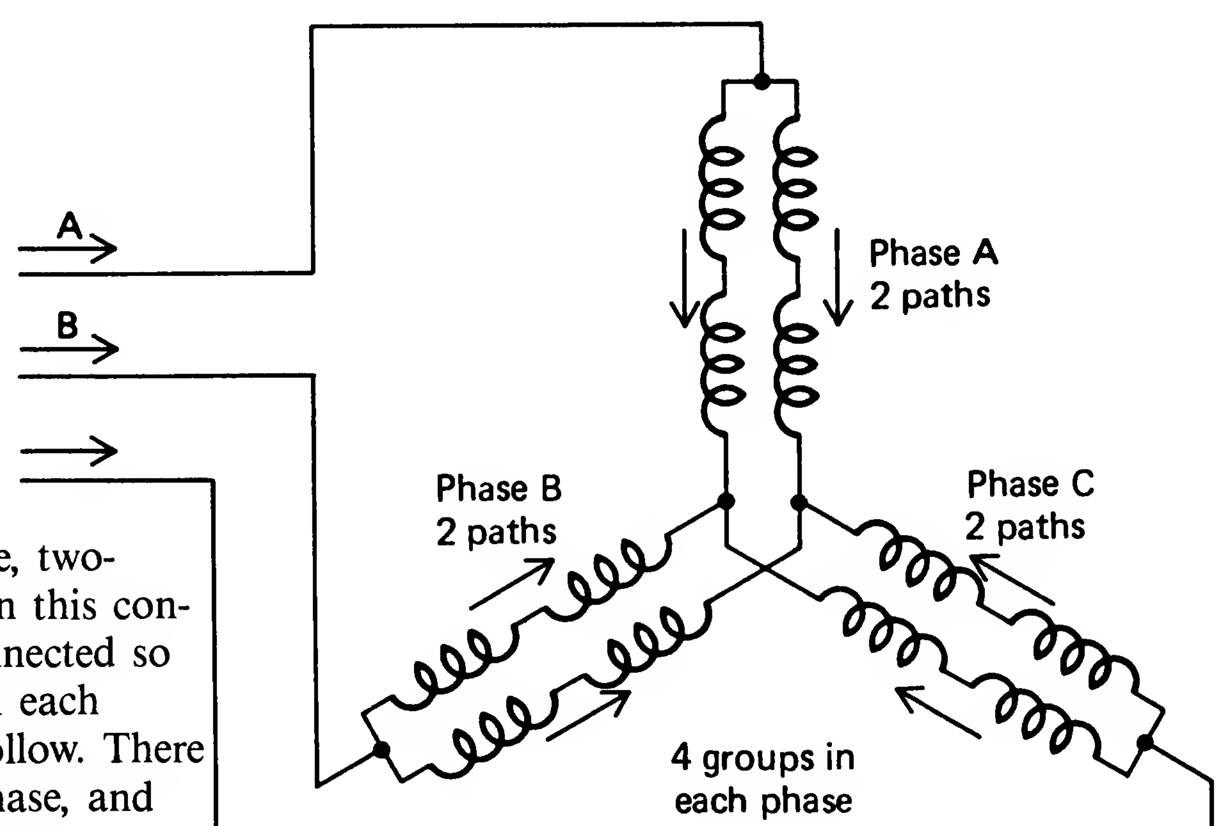


Fig. 3-61. A four-pole, two-parallel (2Y) connection. In this connection the groups are connected so that there are two paths in each phase for the current to follow. There are four groups in each phase, and this forms a four-pole motor.

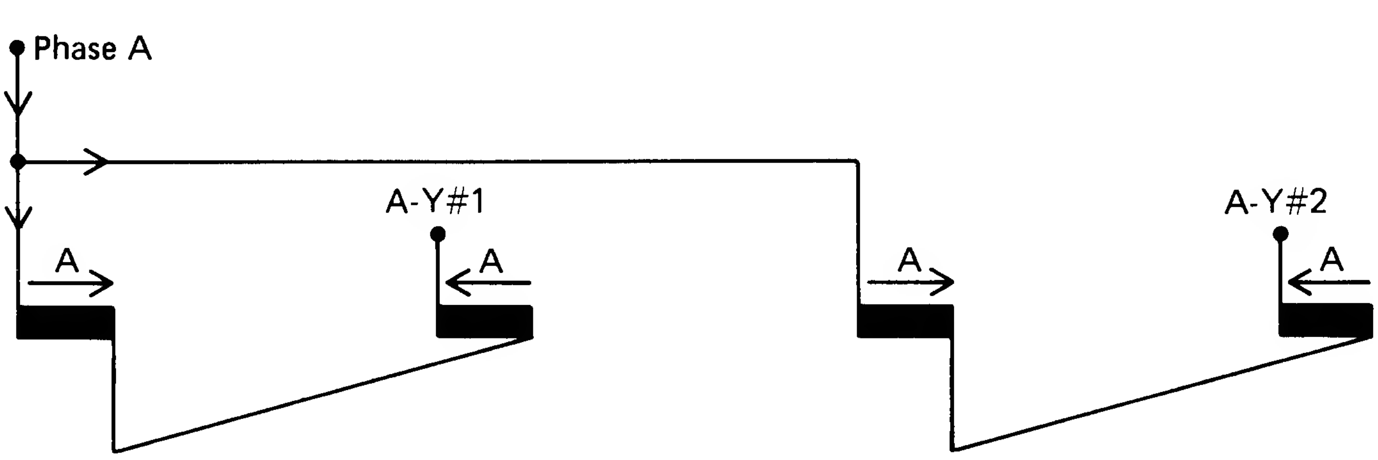


Fig. 3-62a. Phase *A* connection of a two-wye, four-pole, short jumper motor.

Figures 3-60; 3-61; 3-62a

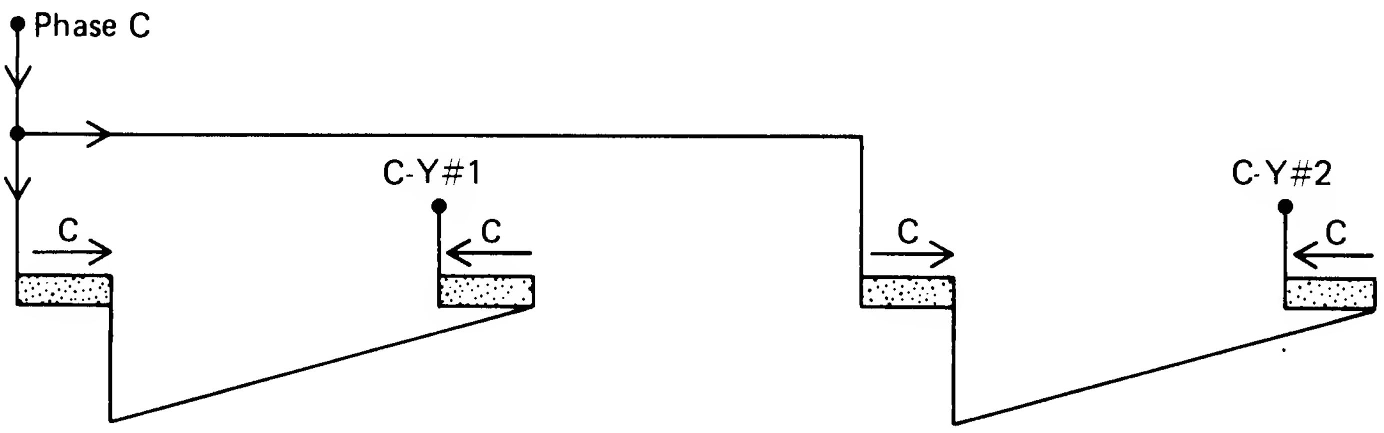


Fig. 3–62b. Phase *C* connection of a two-wye, four-pole, short jumper motor.

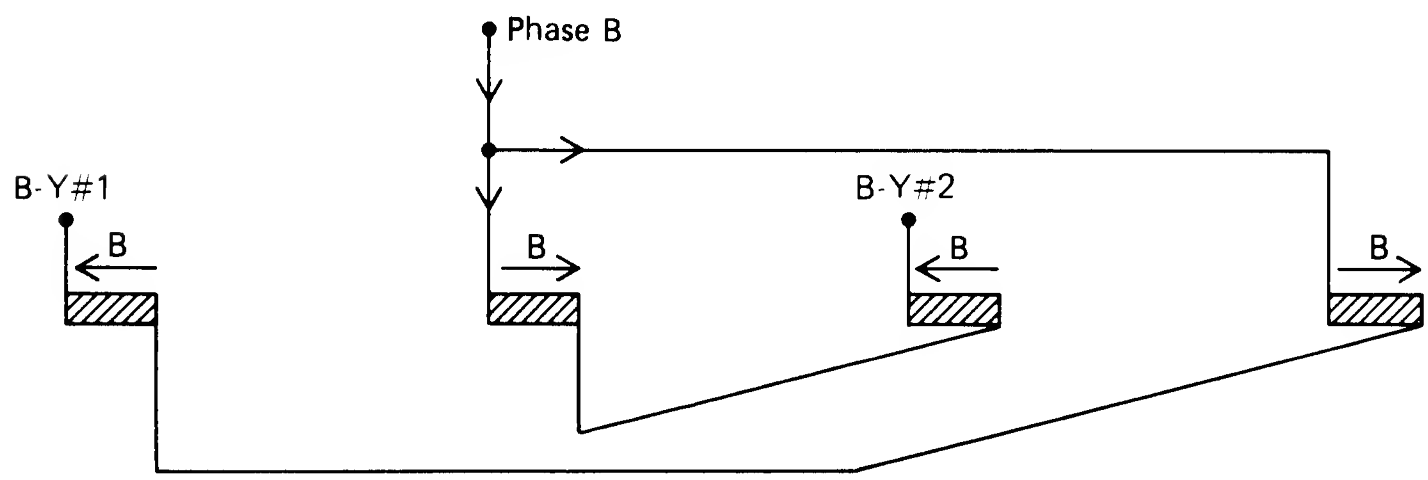


Fig. 3–62c. Phase *B* connection of a two-wye, four-pole, short jumper motor.

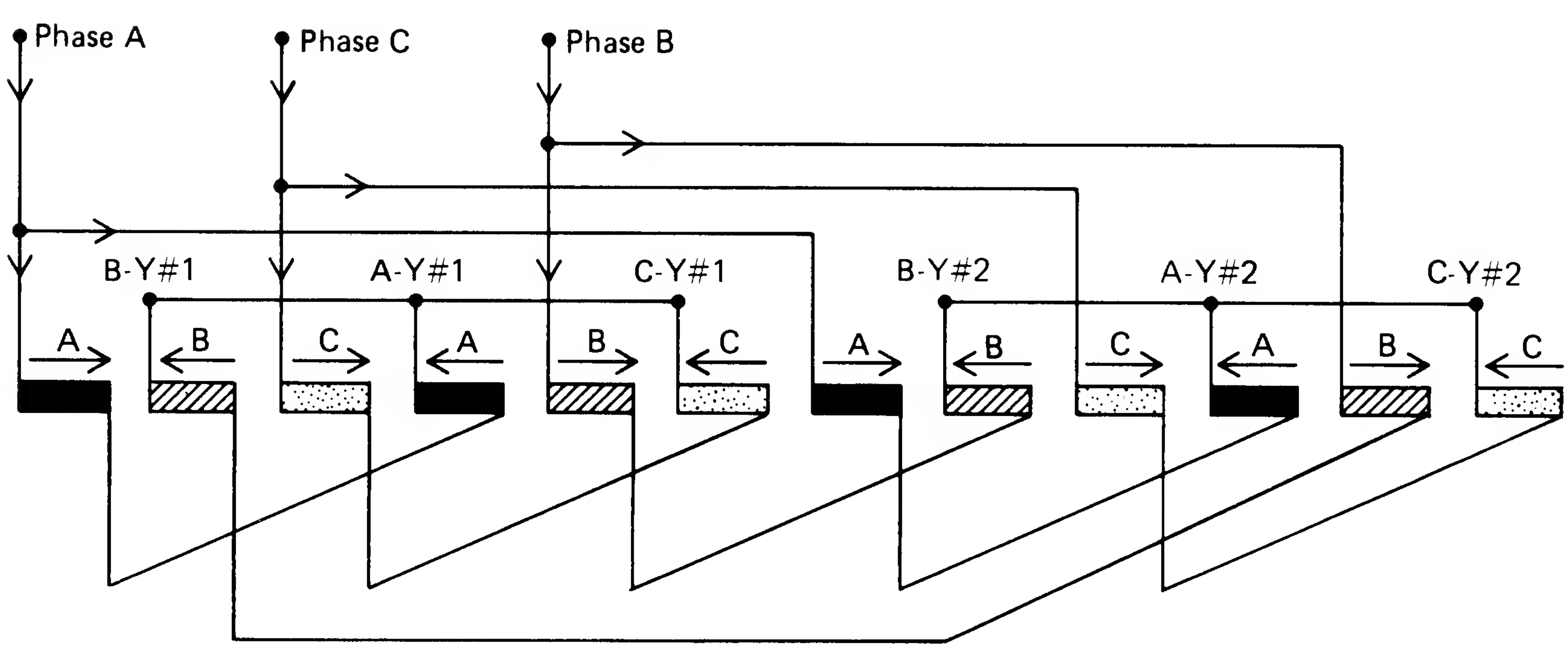


Fig. 3–62d. Three-phase, two-wye, four-pole, short jumper motor.

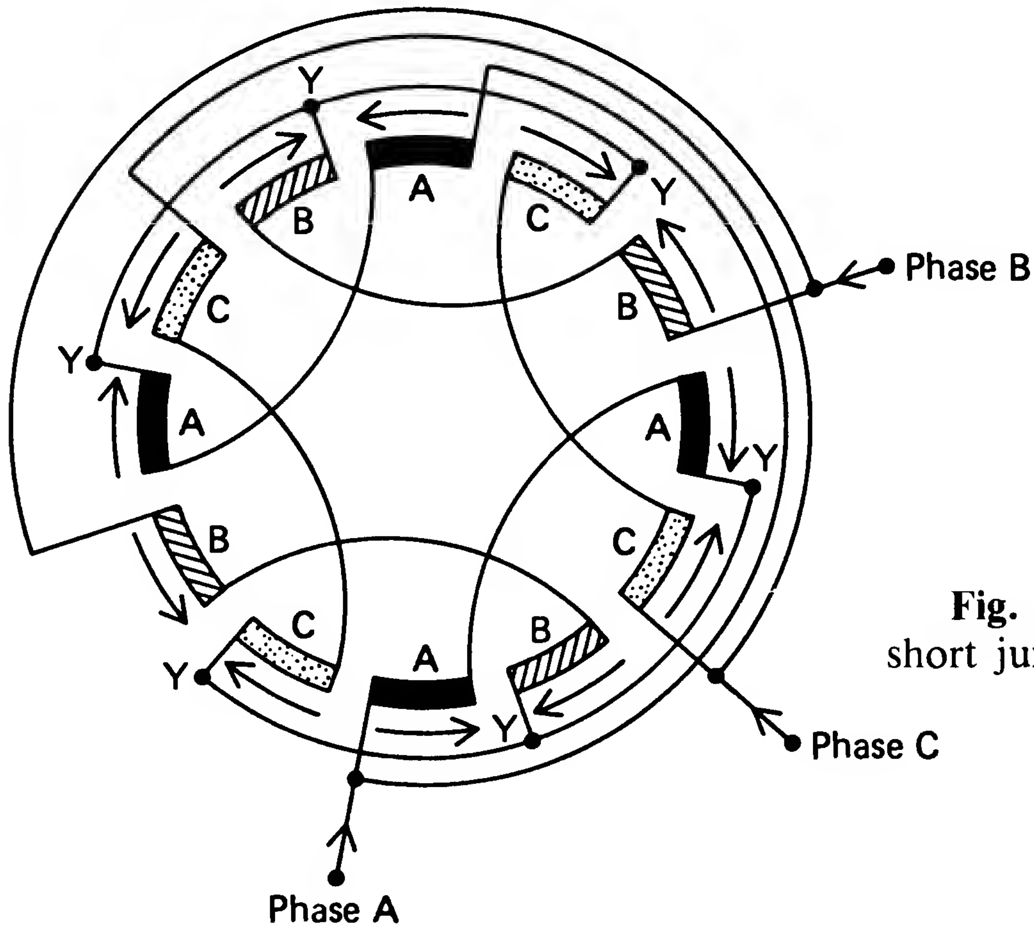


Fig. 3-63. A four-pole, two-wye, short jumper, three-phase diagram.

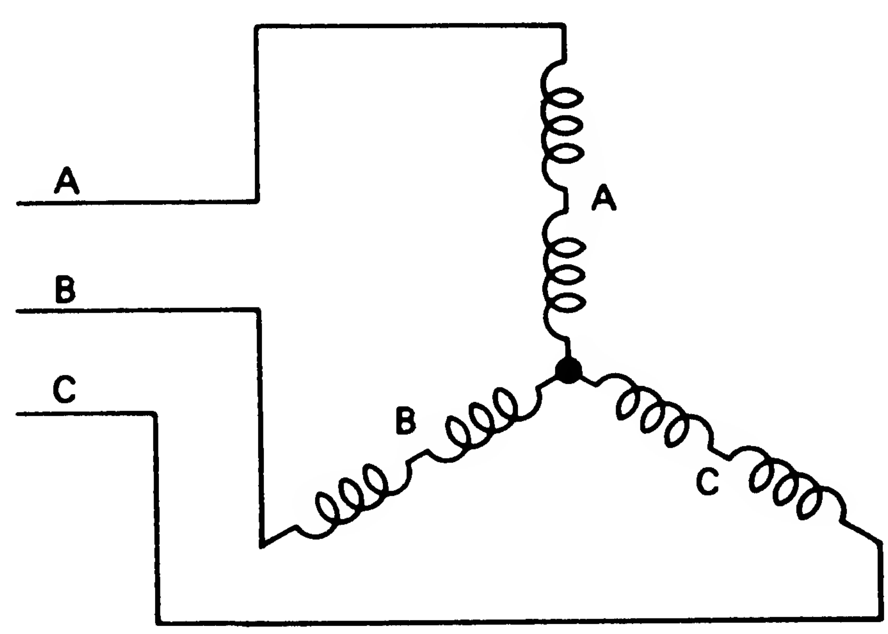


Fig. 3-64. A two-pole, series star (1Y) connection. If only one group is connected to each line, then it is a series star (1Y) connection.

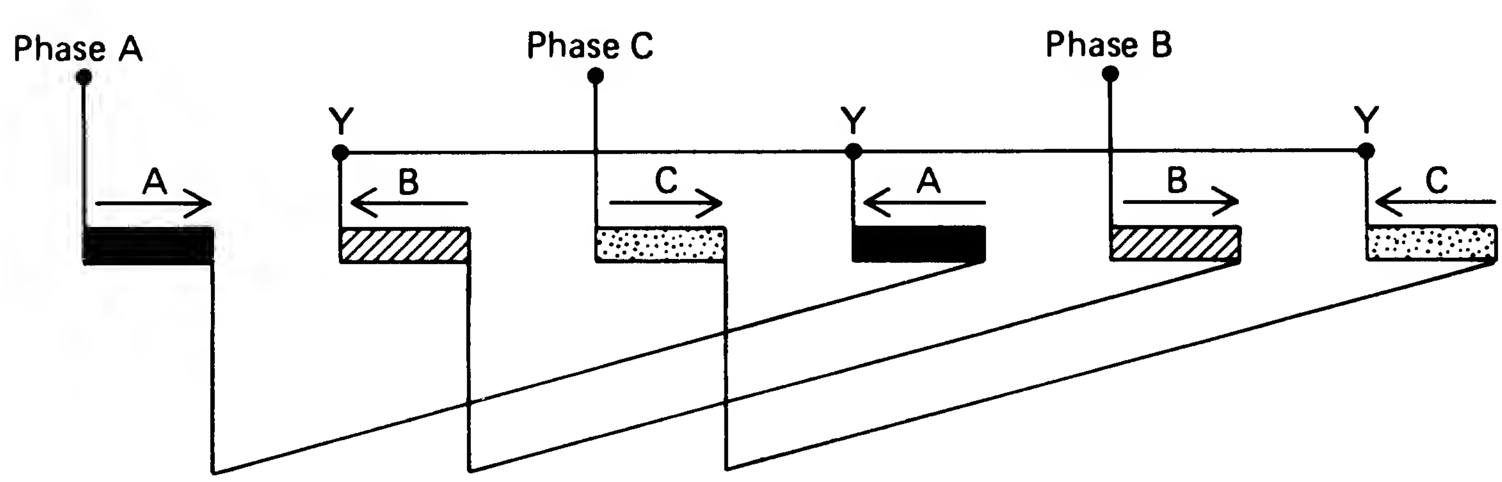


Fig. 3-65. Straight-line diagram of a series-star or wye (1Y) connection.

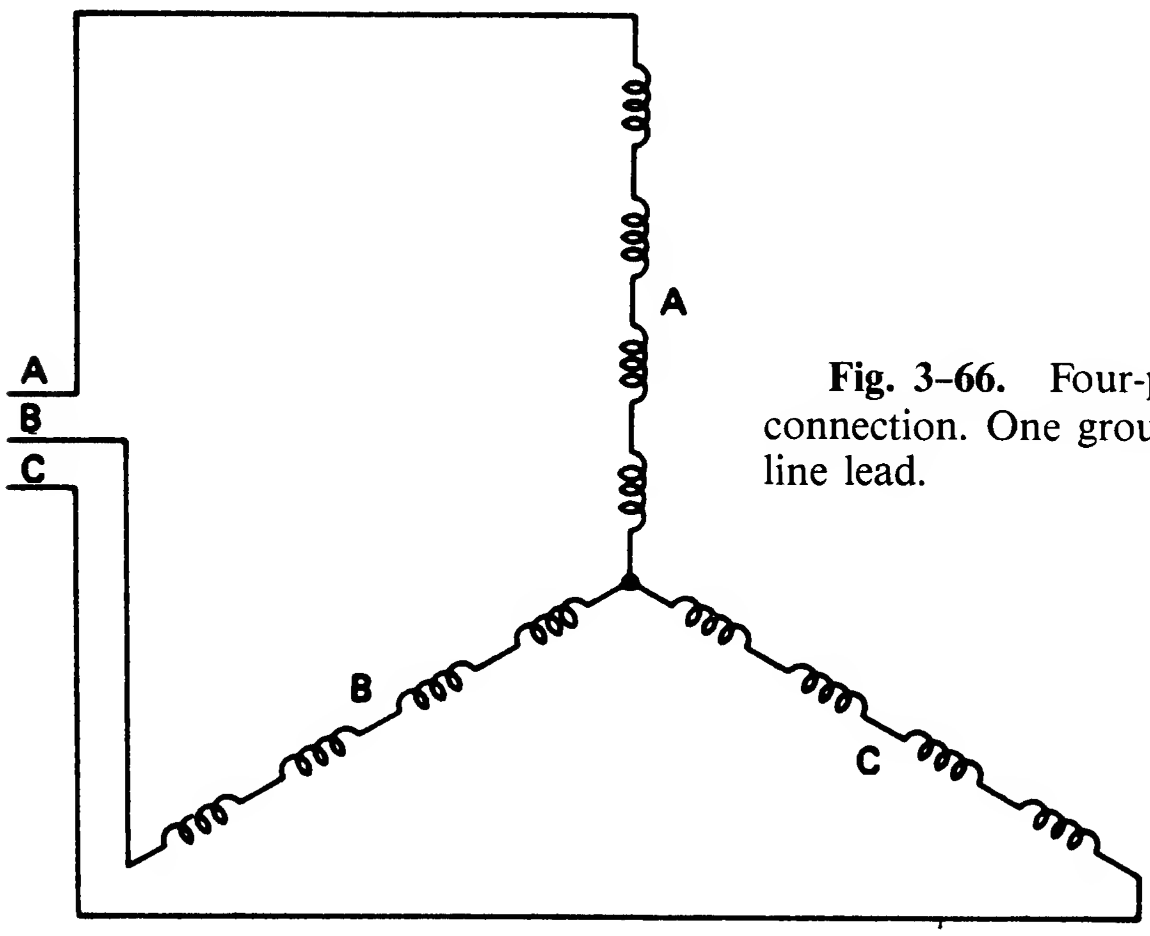


Fig. 3-66. Four-pole series star (1Y) connection. One group connected to each line lead.

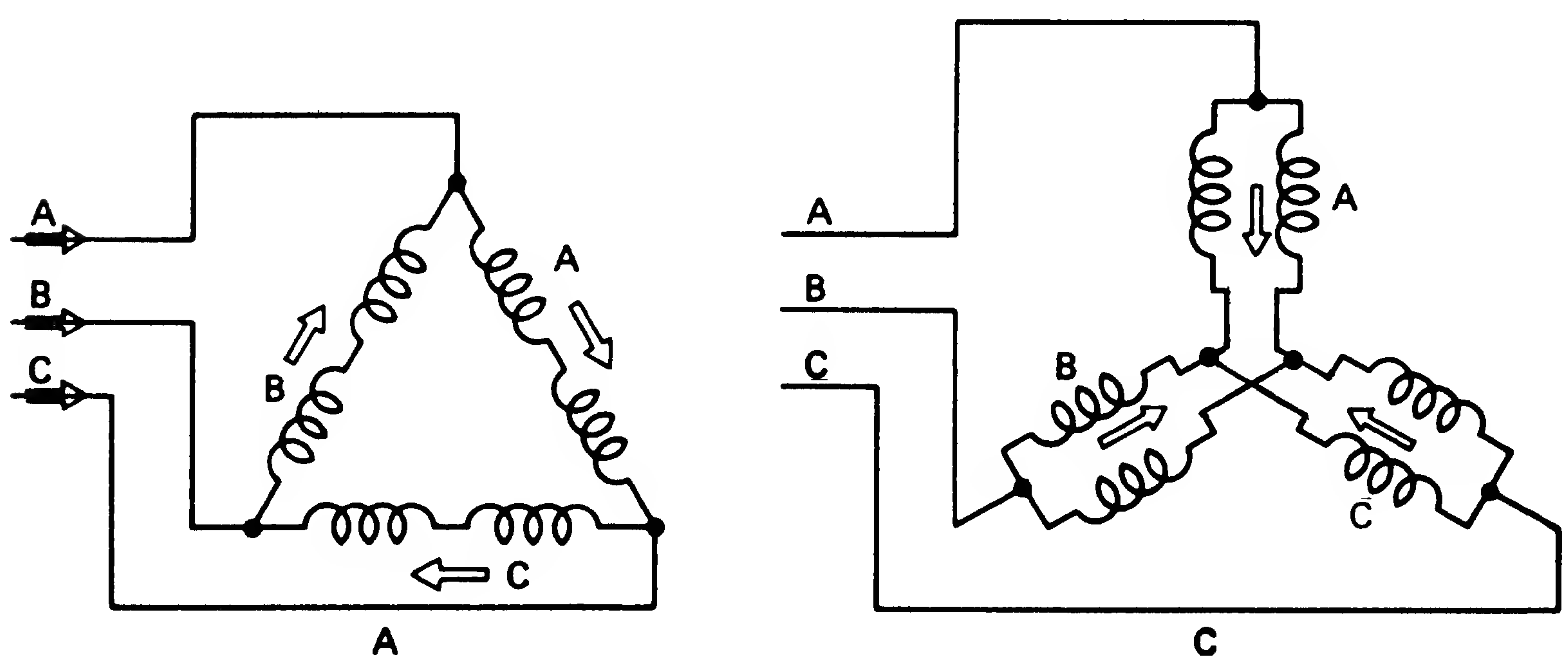
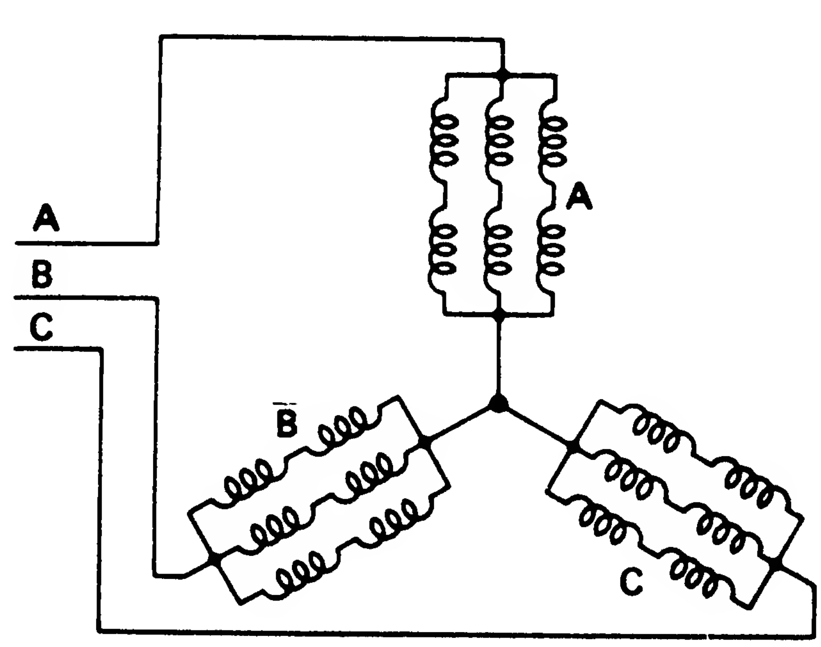


Fig. 3-67. Both methods of connection shown above have each line lead connected to two groups, but the parallel star connection has six groups connected together in two separate wyes.

Fig. 3-68. A three-parallel star (3Y) connection. Each line lead connects to three groups.



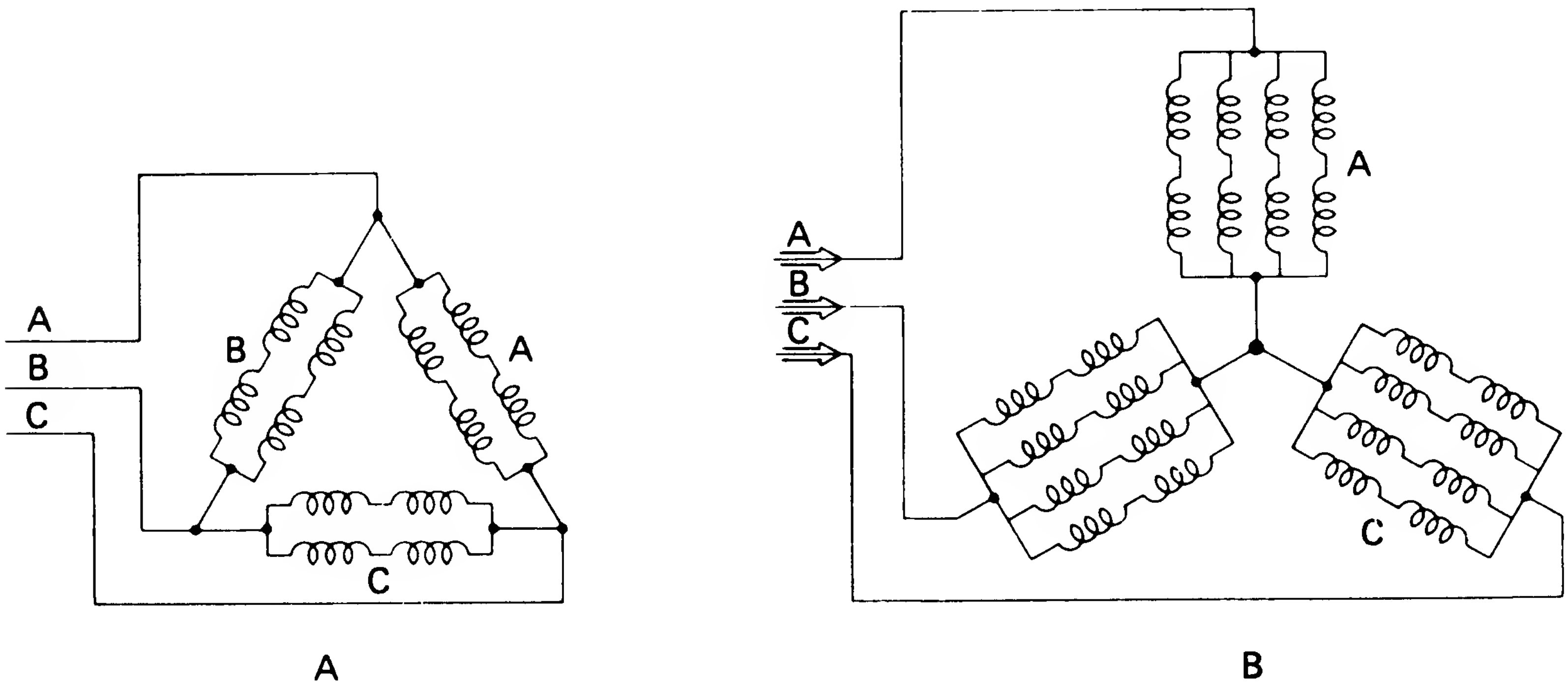


Fig. 3–69. *(A)* shows a four-pole, two-parallel delta 2Δ connection with each line lead connected to four groups. *(B)* shows an eight-pole, four-parallel star (4Y) connection. Both methods of connection shown have each line lead connected to four groups, but the four-parallel star (4Y) connection has twelve groups connected together.

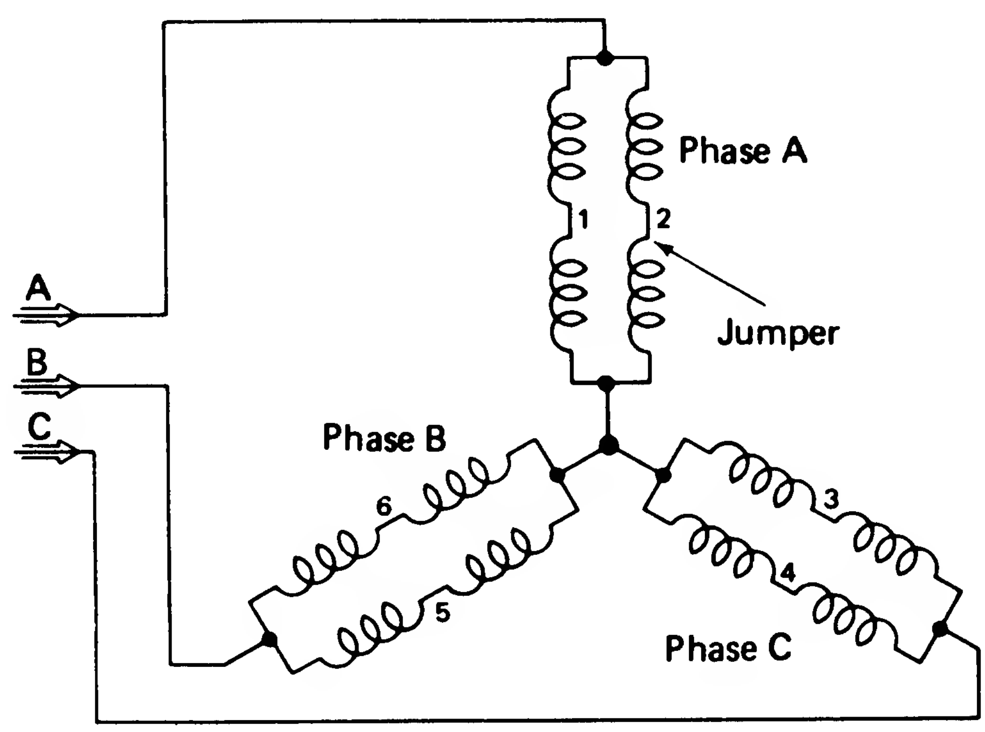


Fig. 3–70. The four-pole, two-parallel star (2Y) connection has six jumpers.

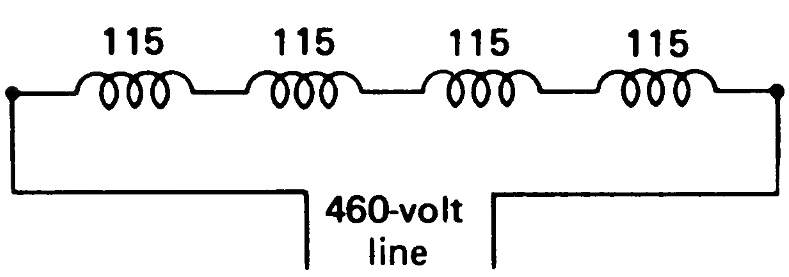


Fig. 3–71. Four coils connected in series for 460-volt line. The voltage in each coil is 115.

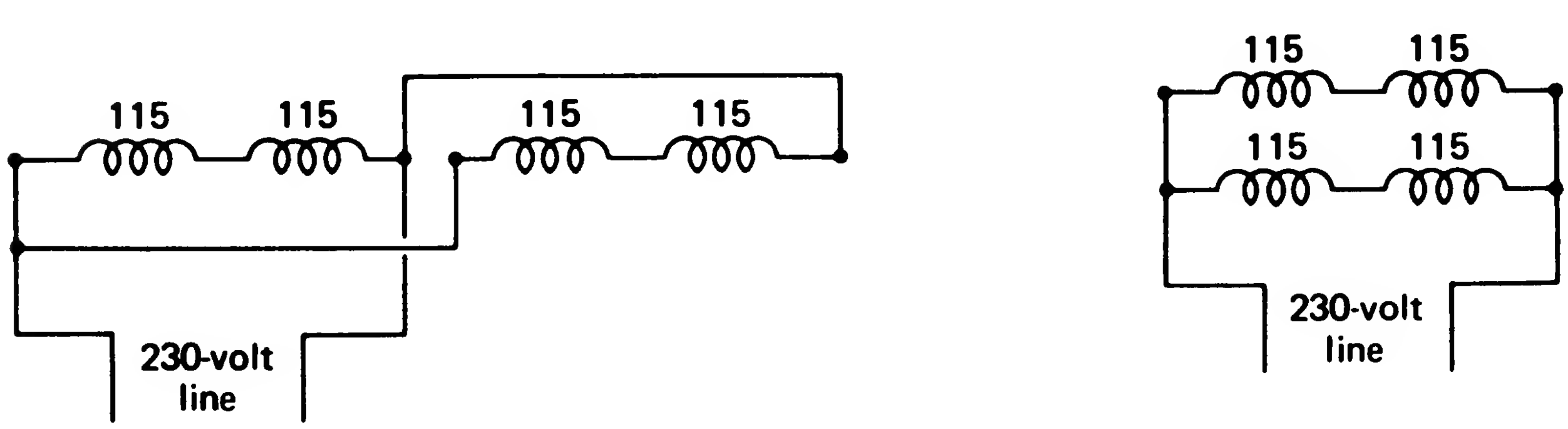
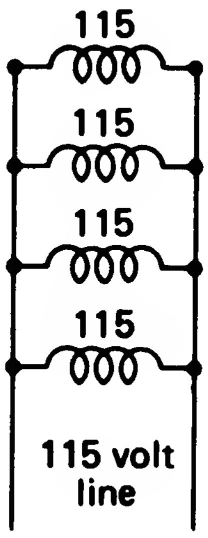


Fig. 3–72. Four coils connected two-parallel for a 230-volt line. Each coil still receives 115 volts.

Figures 3–69; 3–70; 3–71; 3–72



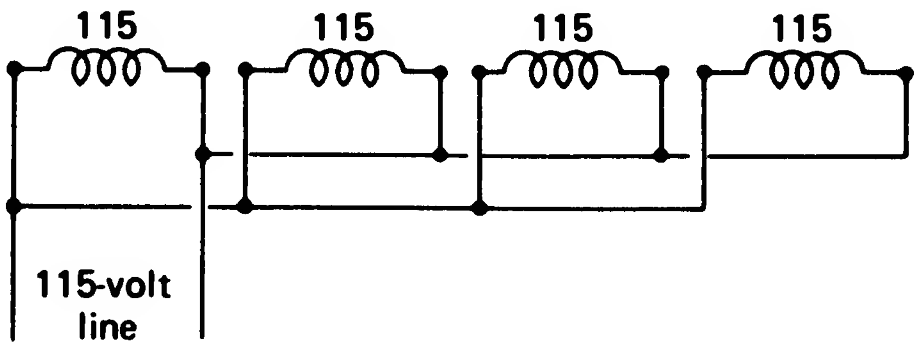


Fig. 3-73. The four coils of **Fig. 3-72** connected for 115-volt operation.

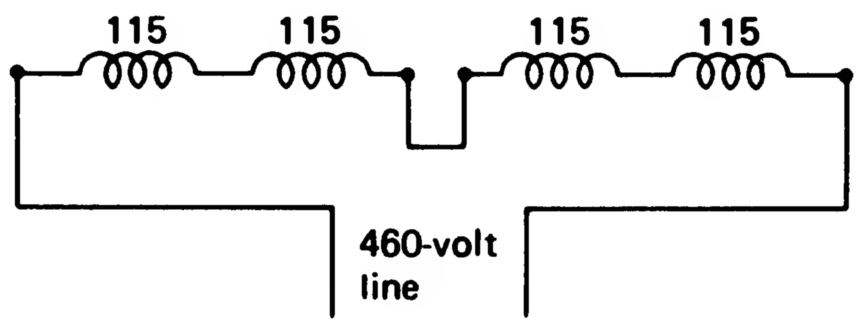


Fig. 3-74. Series connection of coils for 460-volt operation.

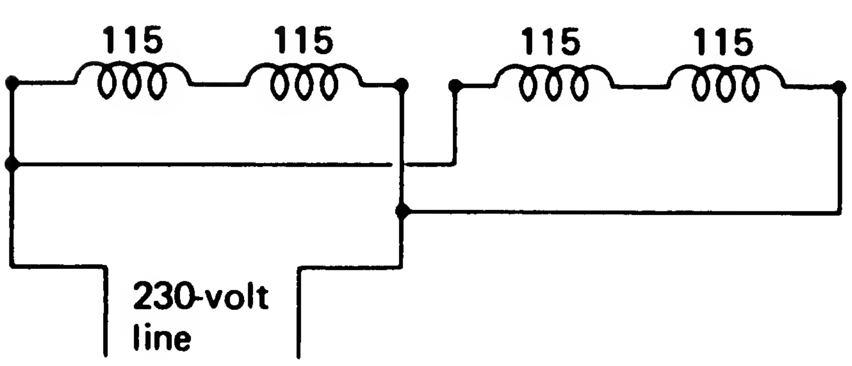


Fig. 3-75. Two sets of coils in parallel for 230-volt operation.

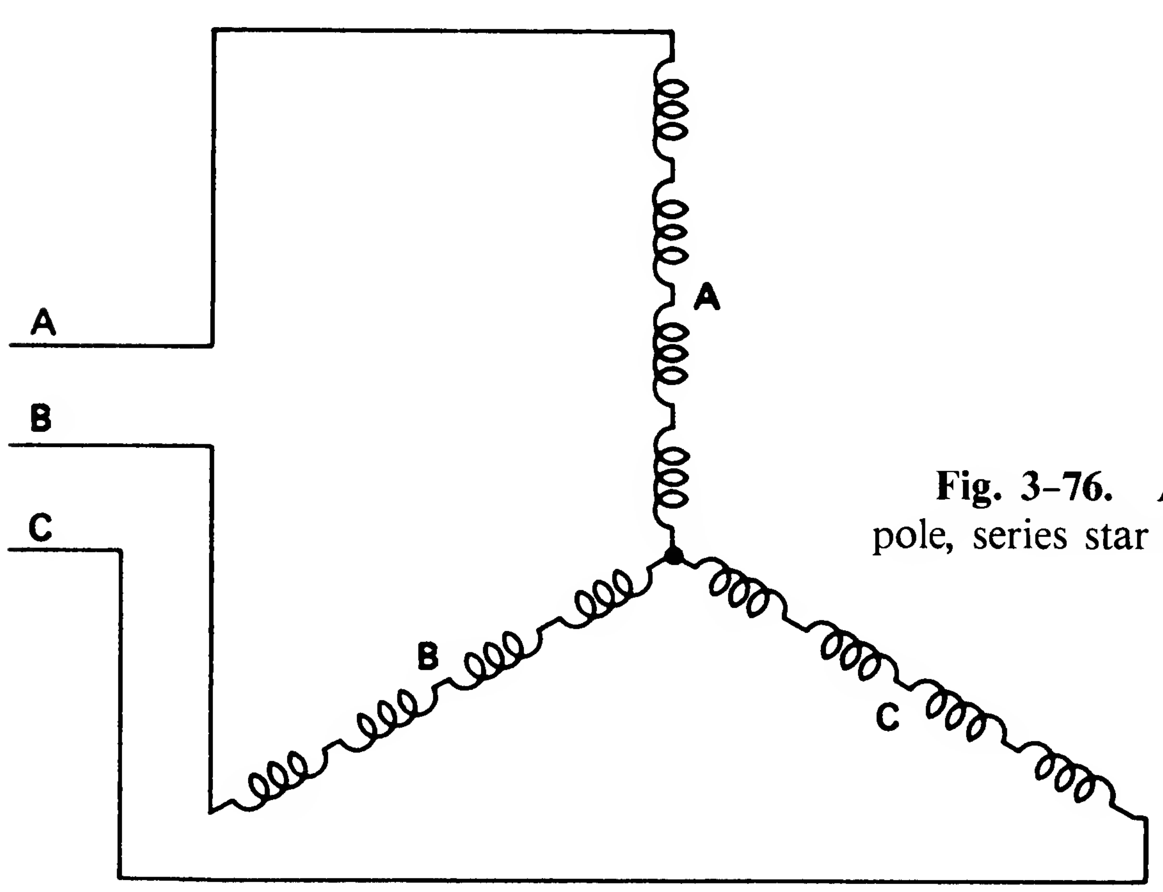


Fig. 3-76. A three-phase, four-pole, series star (1Y) connection.

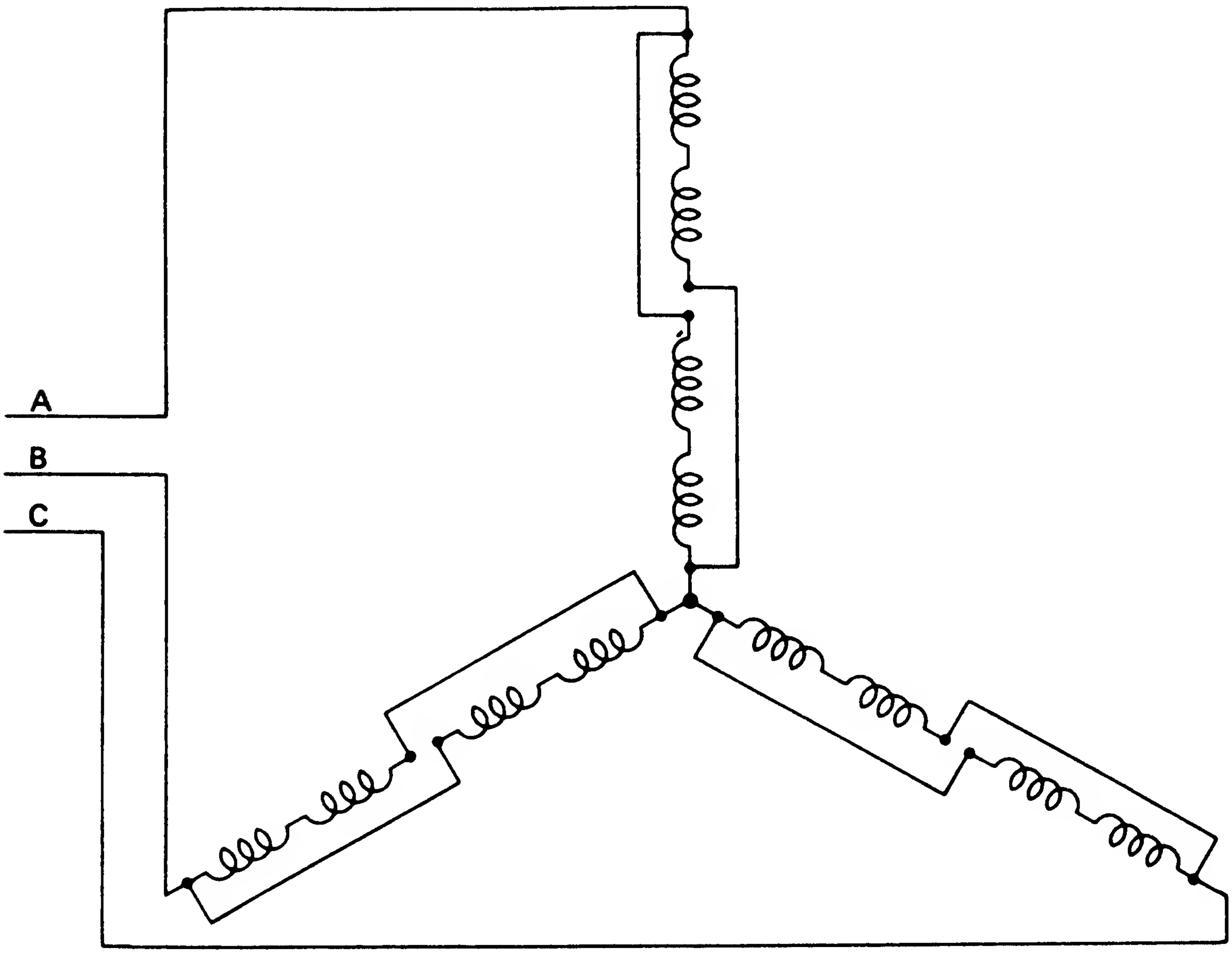


Fig. 3–77. A three-phase, four-pole, two-parallel star (2Y) connection with one star point.

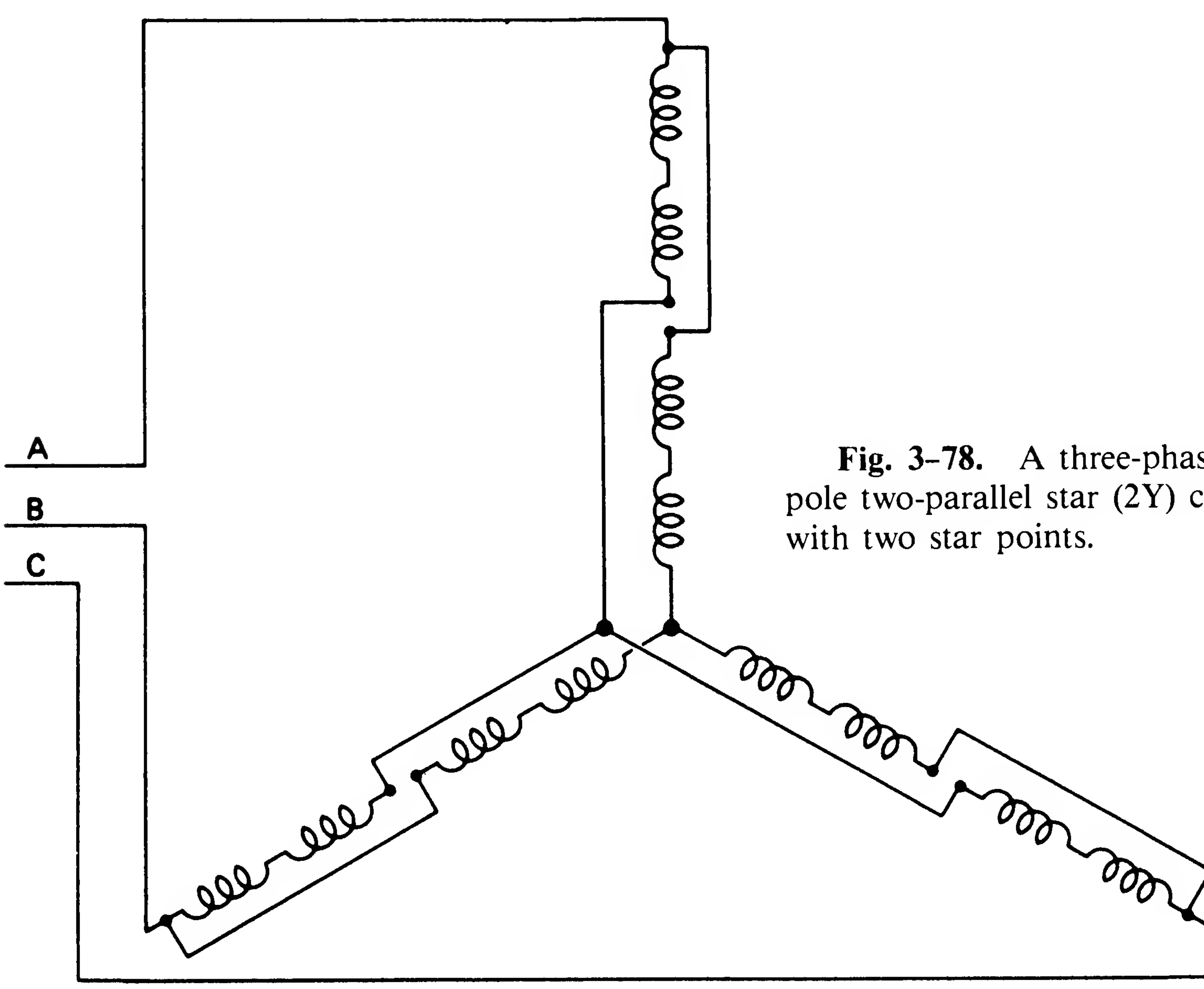
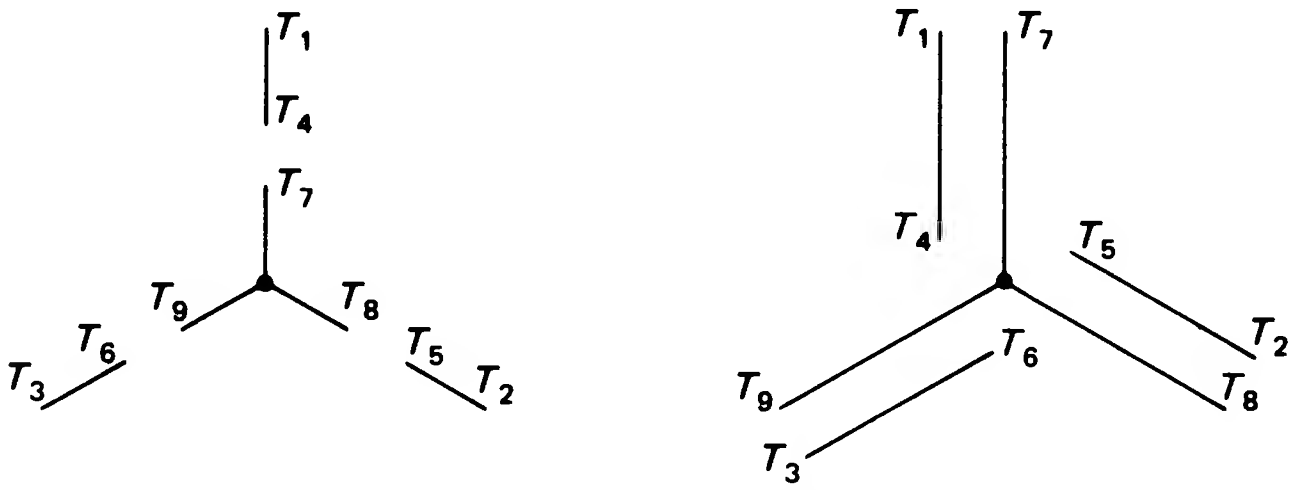
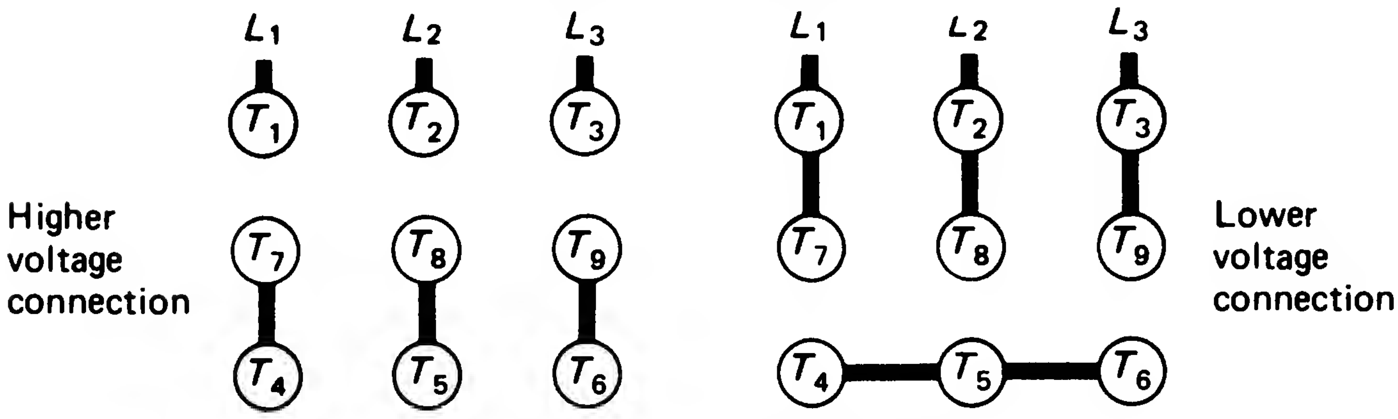


Fig. 3–78. A three-phase, four-pole two-parallel star (2Y) connection with two star points.



Standard markings for Y connected dual voltage motors
Both forms are used



Y connections for dual voltage

Voltage	L_1	L_2	L_3	Tie Together		
Low	$T_1\,T_7$	$T_2\,T_8$	$T_3\,T_9$		$T_4\,T_5\,T_6$	
High	T_1	T_2	T_3	$T_4\,T_7$	$T_5\,T_8$	$T_6\,T_9$

Table of connections

Fig. 3–79. Markings and connections for Y connected dual-voltage motor.

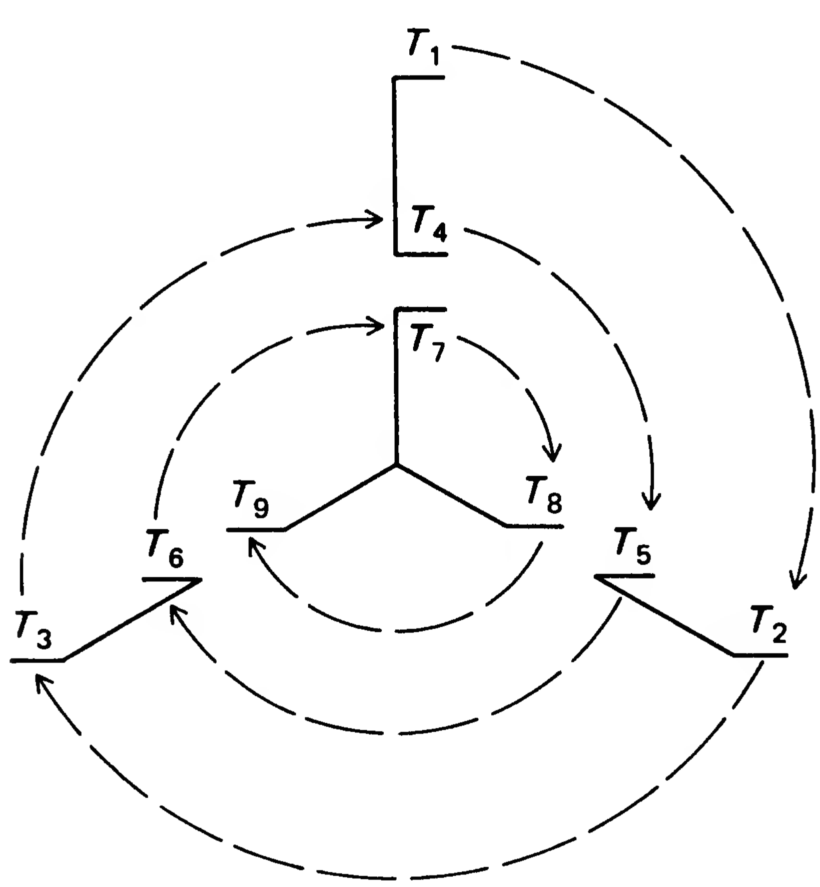


Fig. 3–80a. The spiral method of finding the proper numbers for a nine-lead, one- and two-wye schematic.

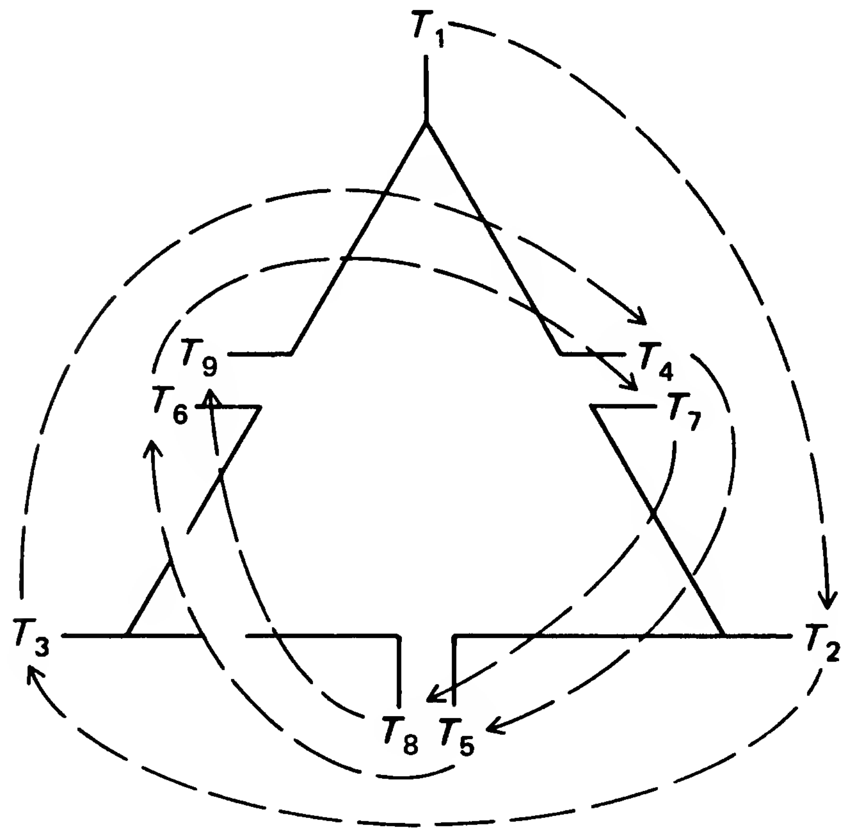


Fig. 3-80b. The spiral method of finding the proper numbers for a nine-lead, one- and two-delta schematic.

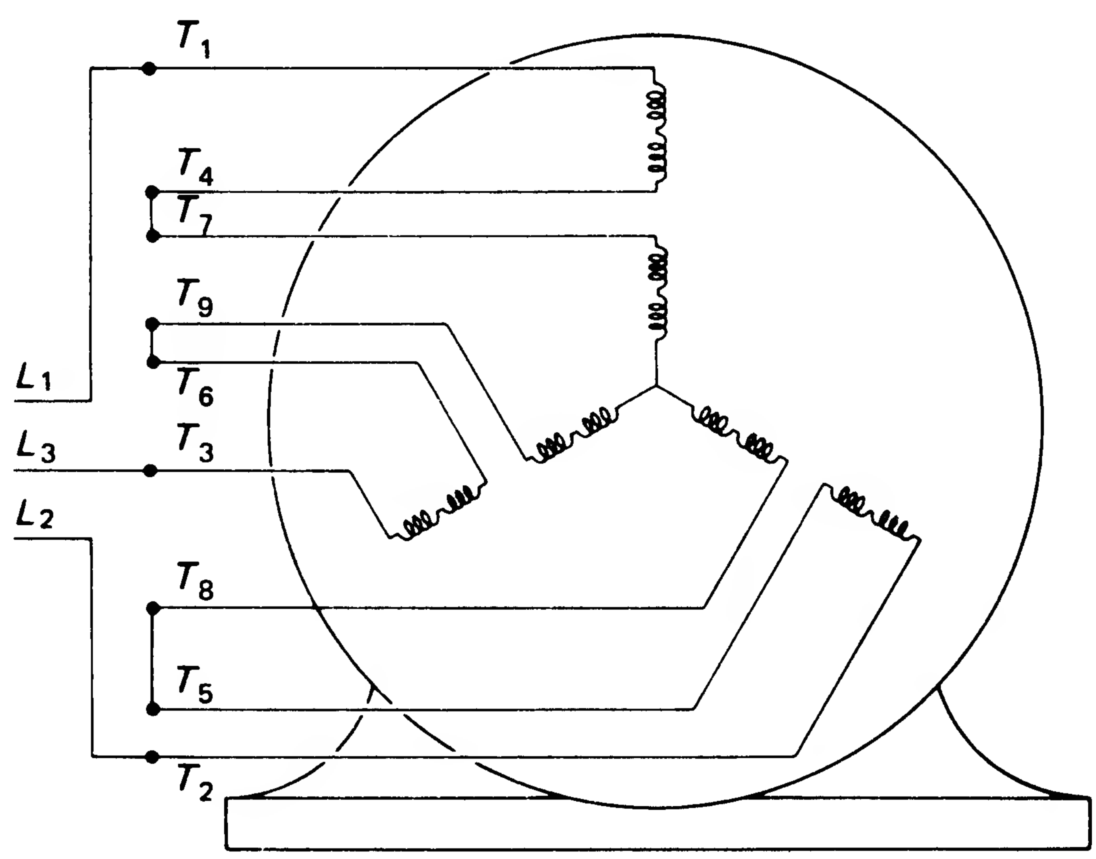


Fig. 3-81. A two-voltage star (wye) motor with groups connected in series for high-voltage operations.

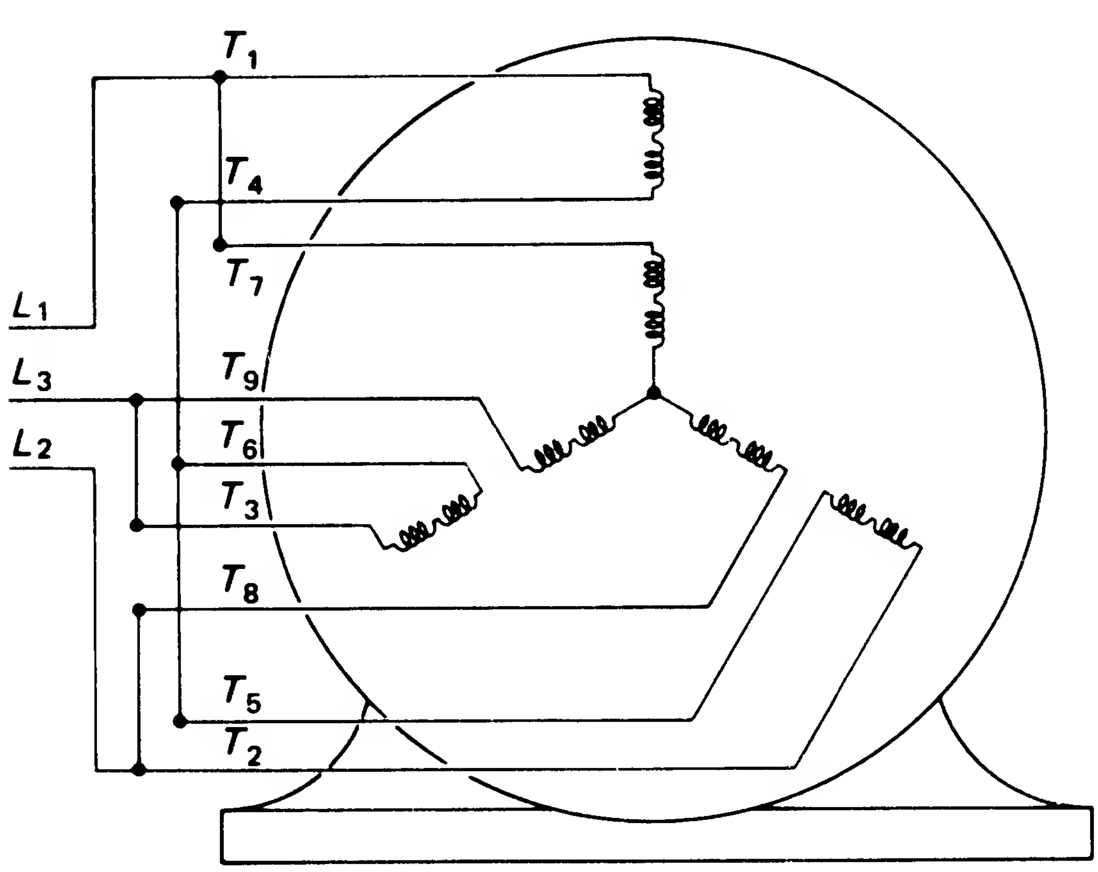


Fig. 3-82. A two-voltage star (wye) motor with groups connected in parallel for low voltage. The common connection of *4, 5,* and *6* forms an external star.

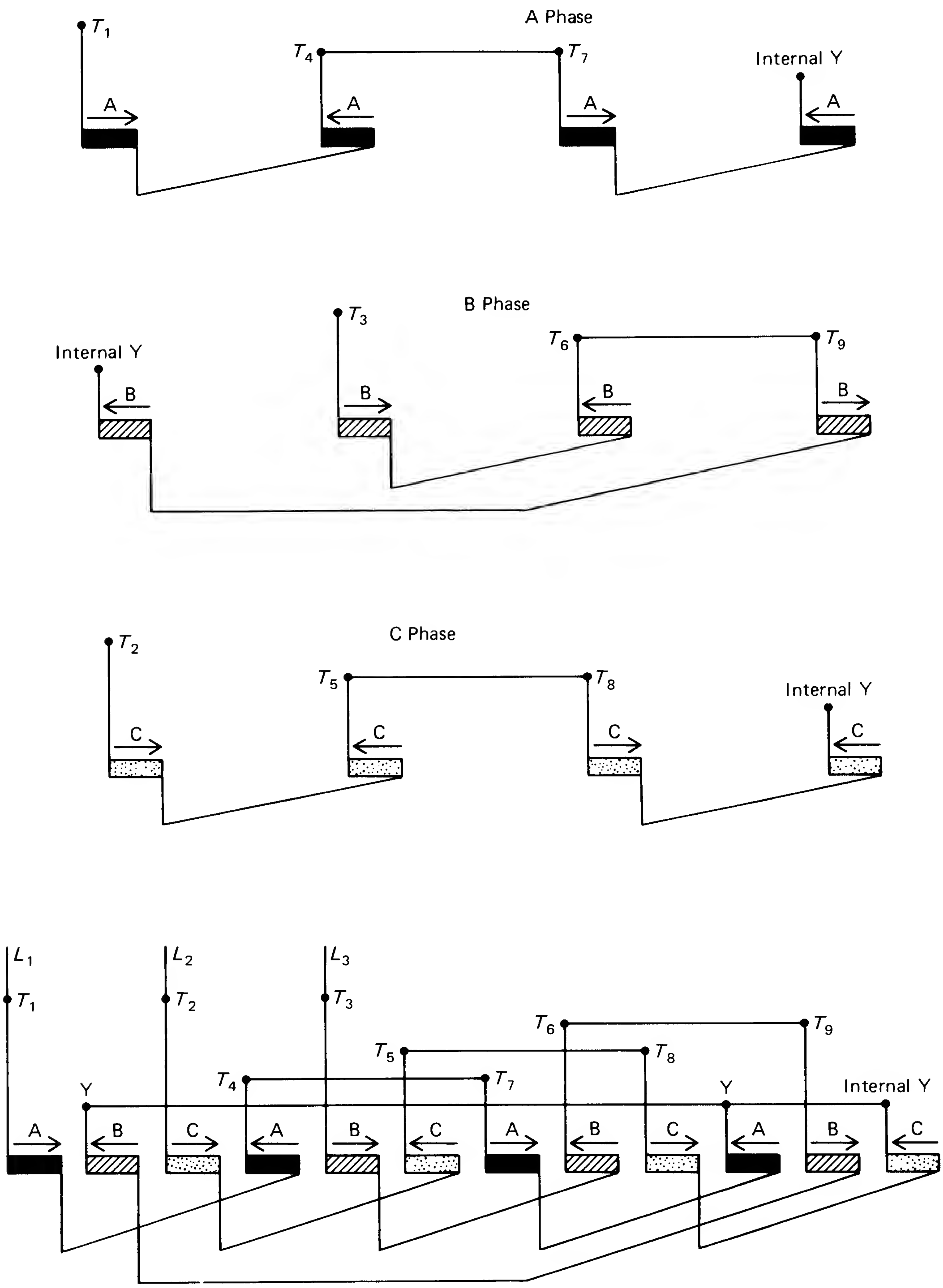


Fig. 3-83. A three-phase, four-pole, two-voltage, short jumper, one- and two-wye motor connected for high voltage. Each phase is shown separately above and also connected for high voltage.

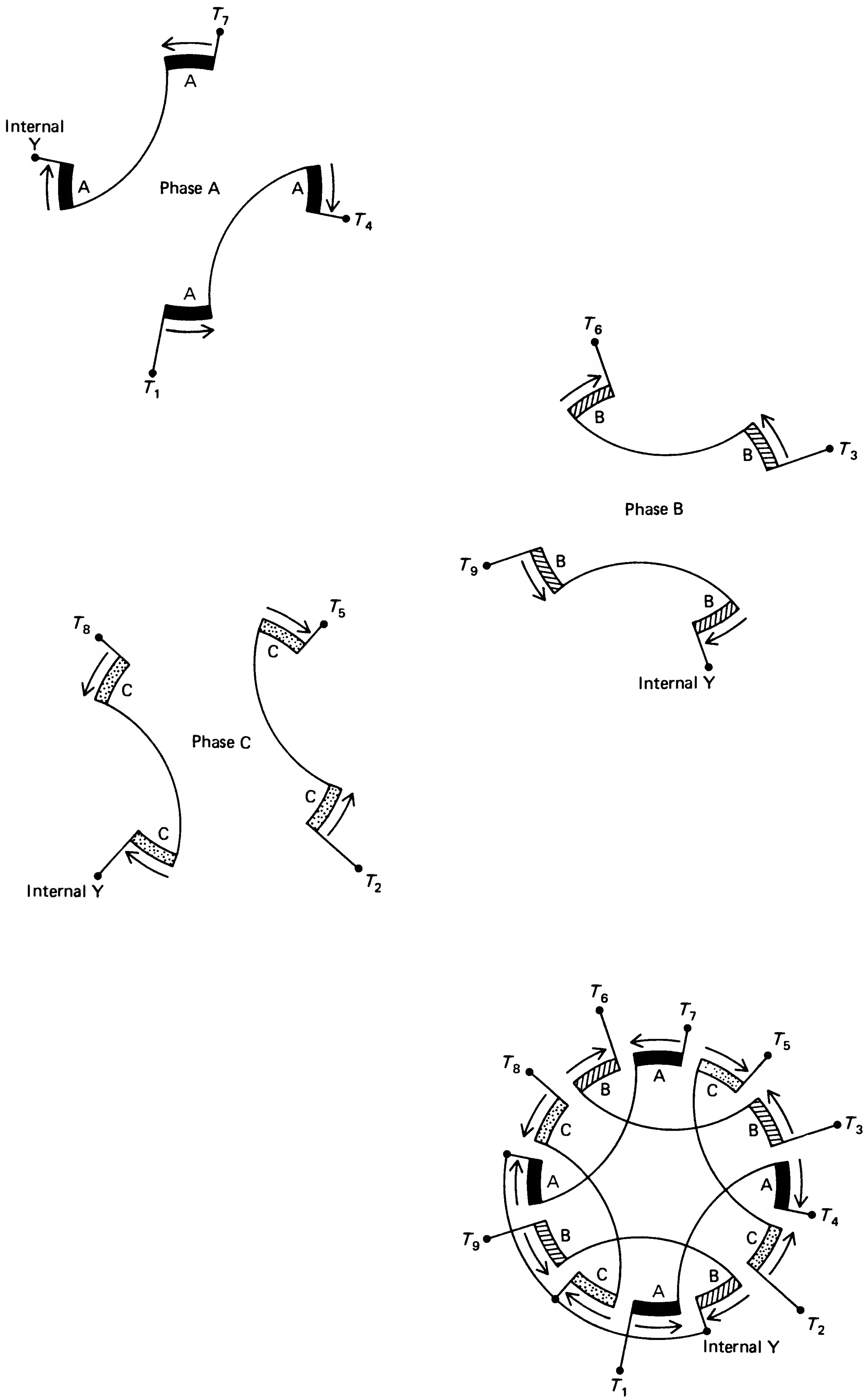
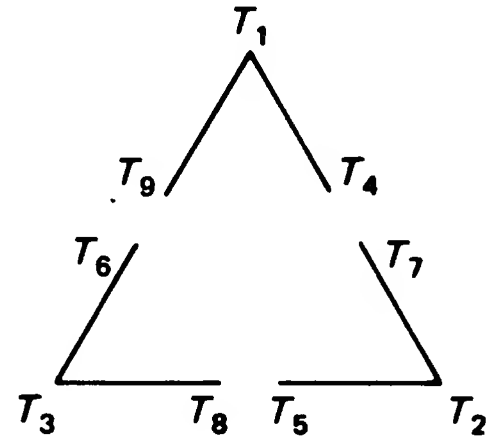
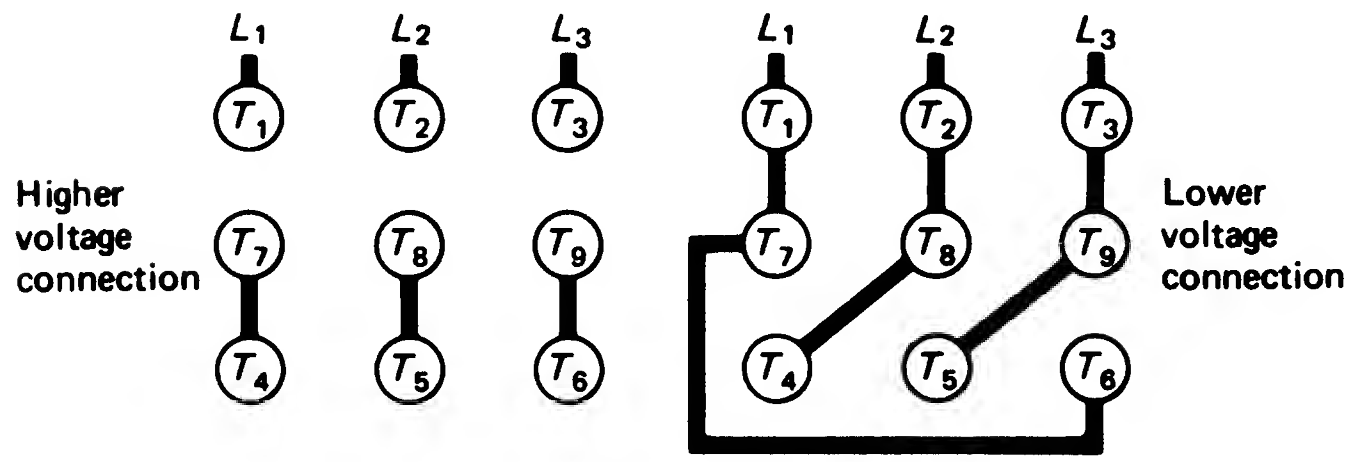


Fig. 3-84. A circular diagram of a four-pole, two-voltage, short jumper, one- and two-wye motor.

Figure 3-84



Standard markings for a delta connected dual voltage motor



Delta connection for dual voltage

Voltage	L_1	L_2	L_3	Tie Together		
Low	$T_1T_6T_7$	$T_2T_4T_8$	$T_3T_5T_9$			
High	T_1	T_2	T_3	T_4T_7	T_5T_8	T_6T_9

Table of connections

Fig. 3-85. Markings and connections for delta-connected dual-voltage motor.

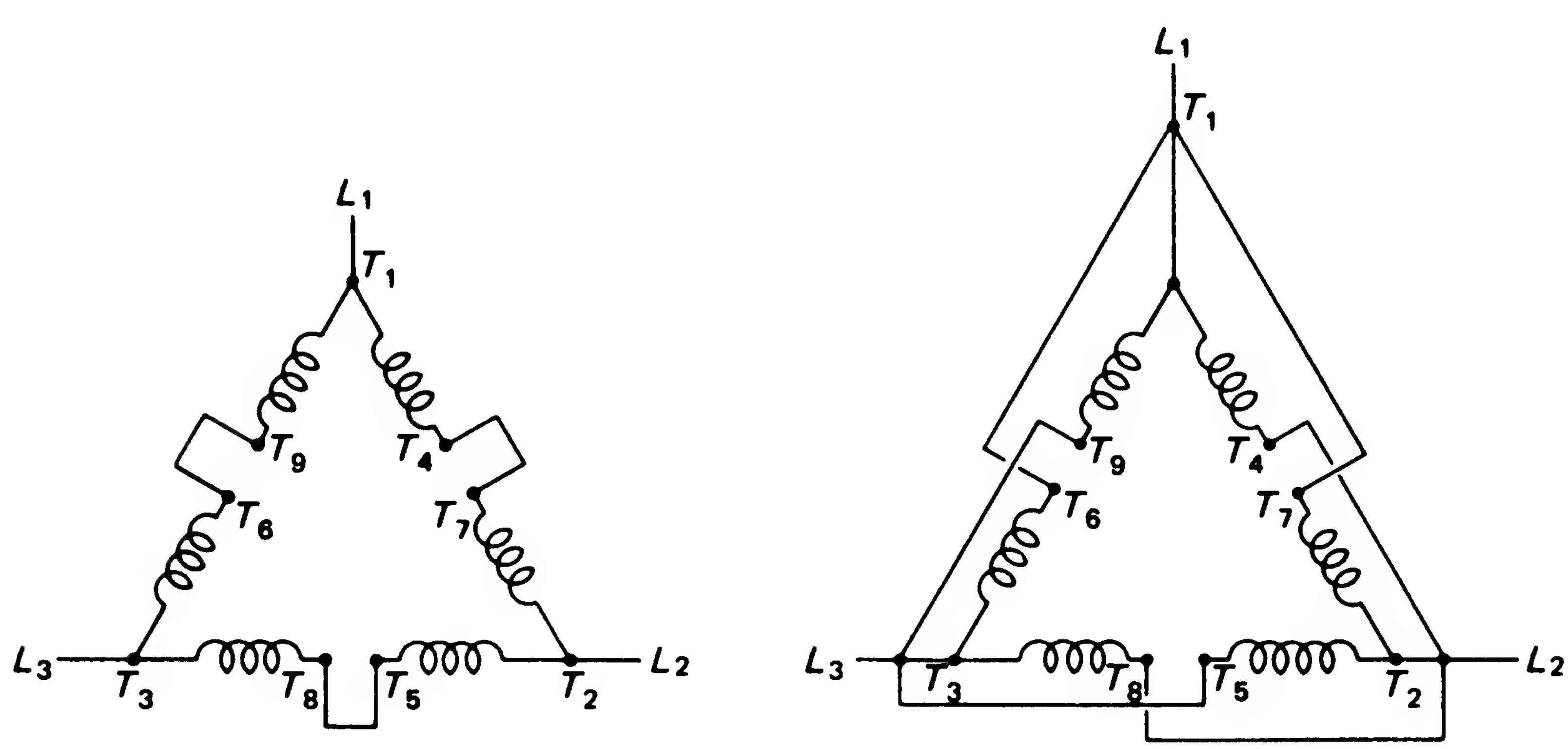


Fig. 3-86. *(Left)* A two-voltage delta connection with groups in series for high-voltage operation. *(Right)* A two-voltage delta connection with groups in parallel for low-voltage operation.

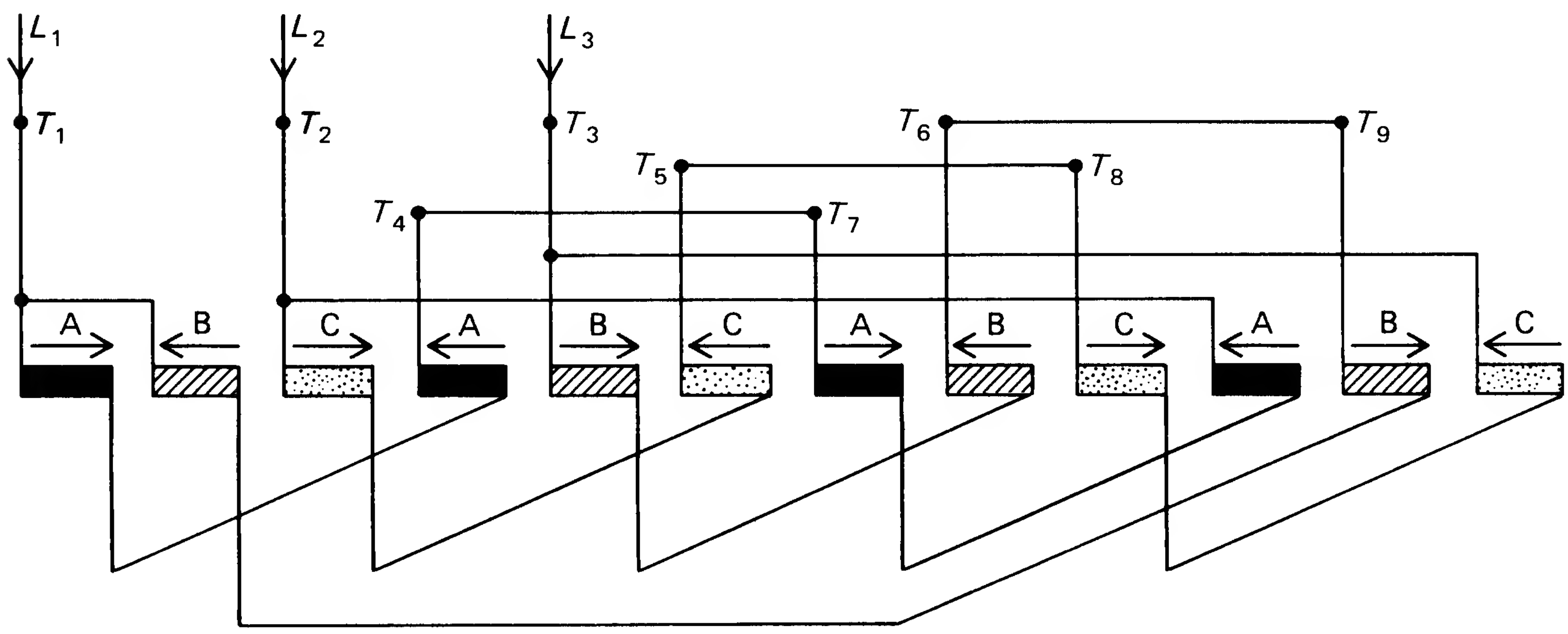
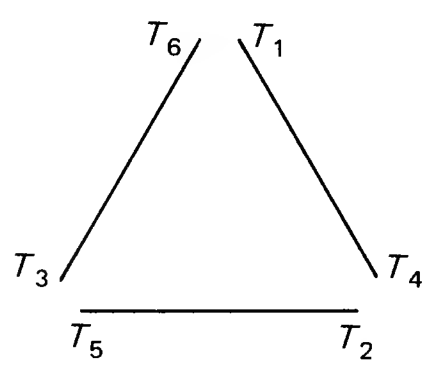


Fig. 3-87. A four-pole, two-voltage, short jumper, one- and two-delta motor connected for high voltage.



Voltage	L_1	L_2	L_3	Tie Together
High	T_1	T_2	T_3	$T_4T_5T_6$
Low	T_1T_6	T_2T_4	T_3T_5	

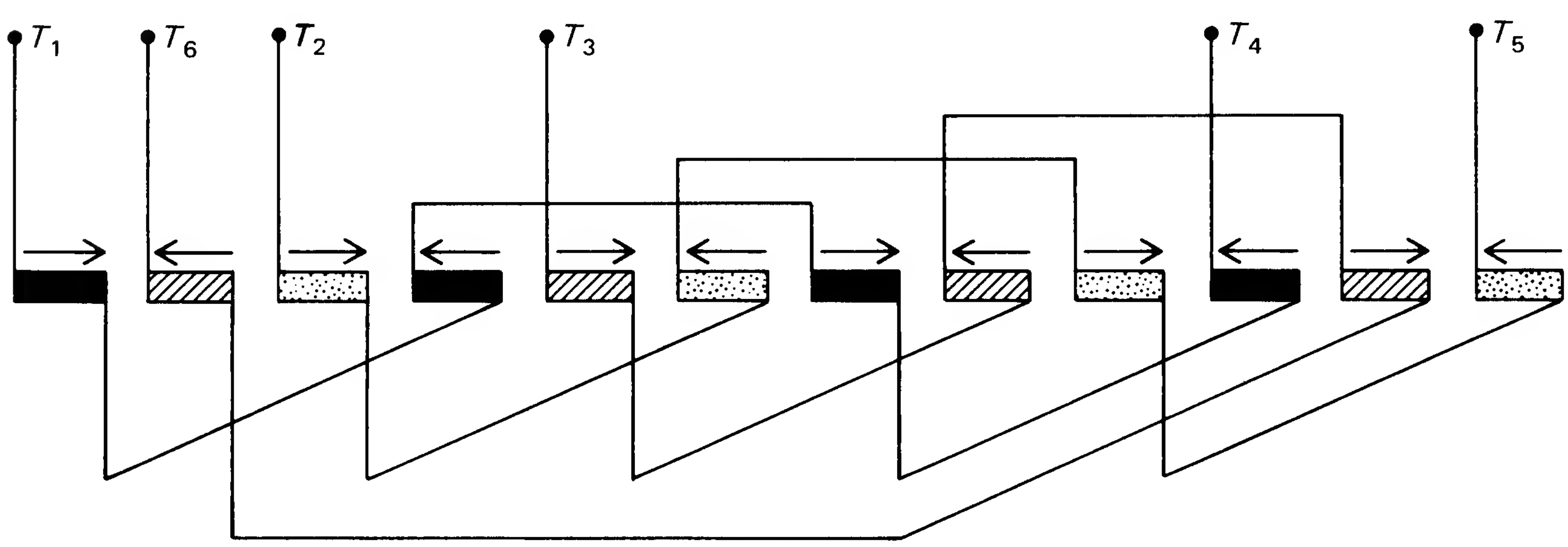


Fig. 3-88. A wye-delta-connected dual-voltage motor with schematic and connection directions.

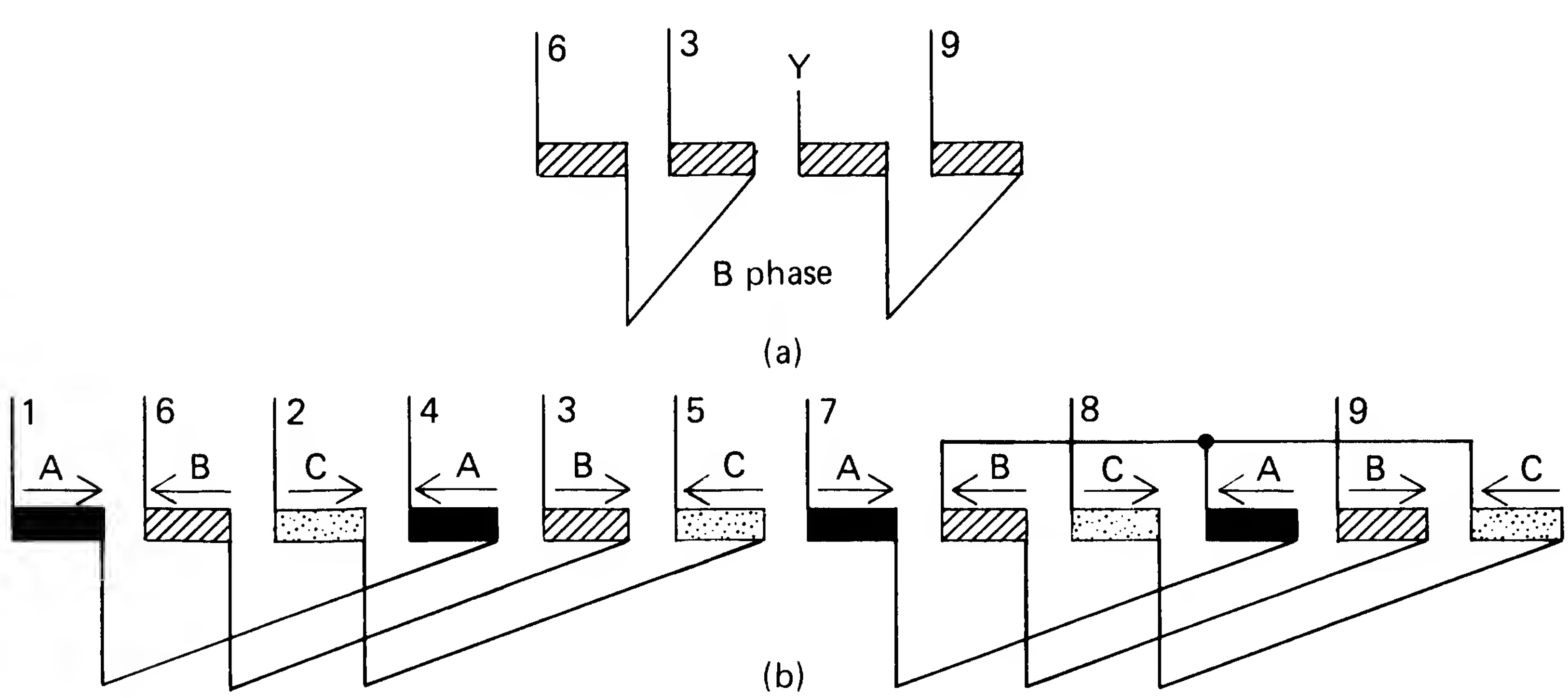


Fig. 3-89a & b. (a) shows the B Phase with the jumper going back to the second group. (b) shows a straight line diagram of this short jumper one and two wye connection.

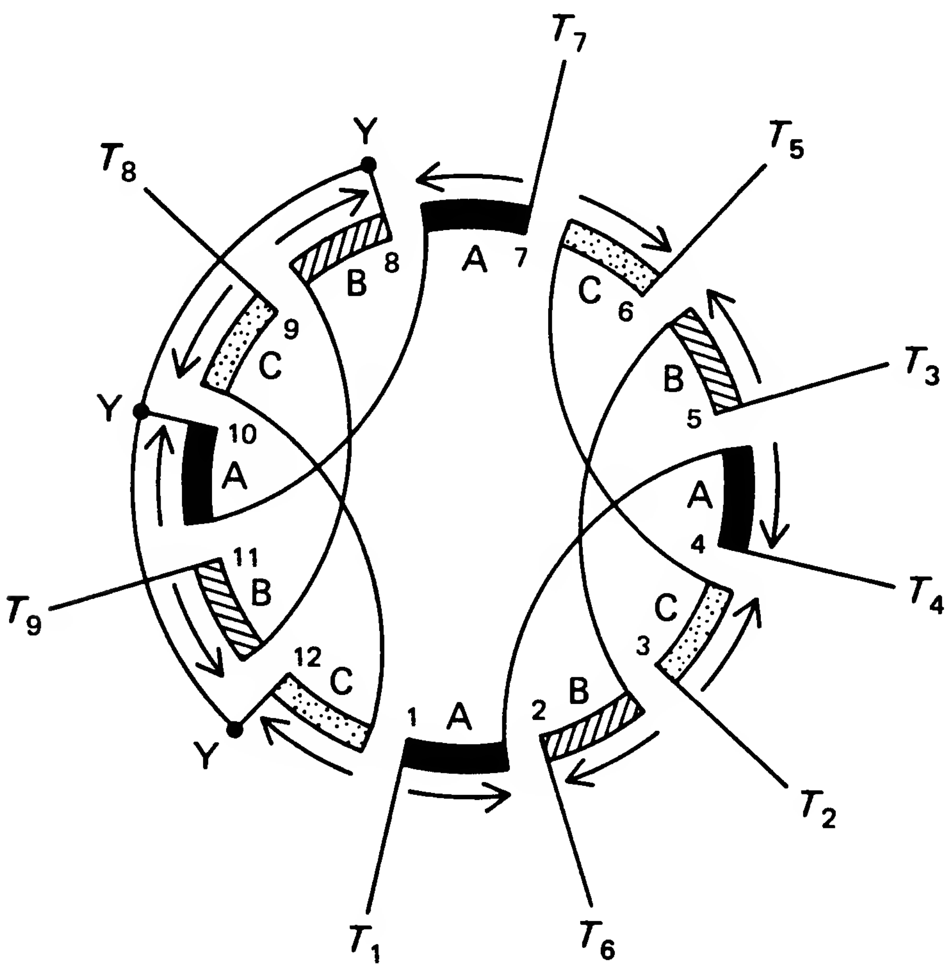


Fig. 3-90. A circular diagram of a one- and two-wye, four-pole, short jumper motor with the *B* phase connected as described in **Fig. 3-89b.**

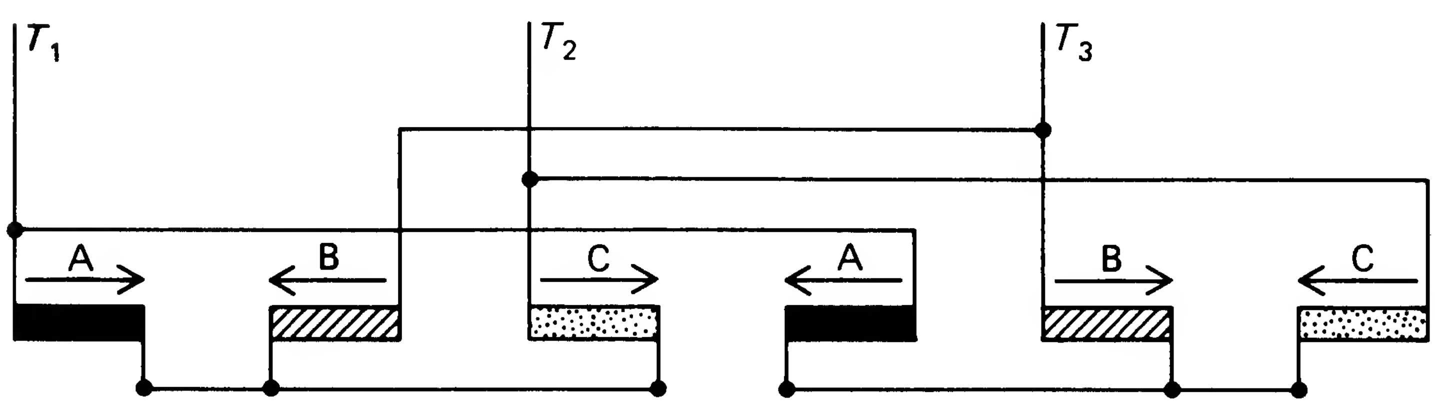


Fig. 3-91a. A two-pole, two-wye motor.

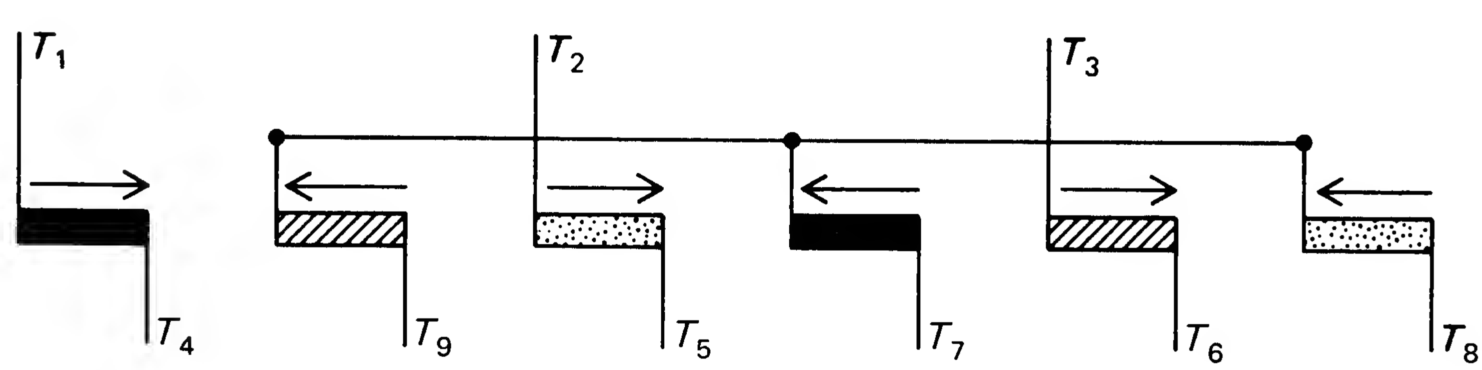


Fig. 3-91b. A two-pole, one- and two-wye motor.

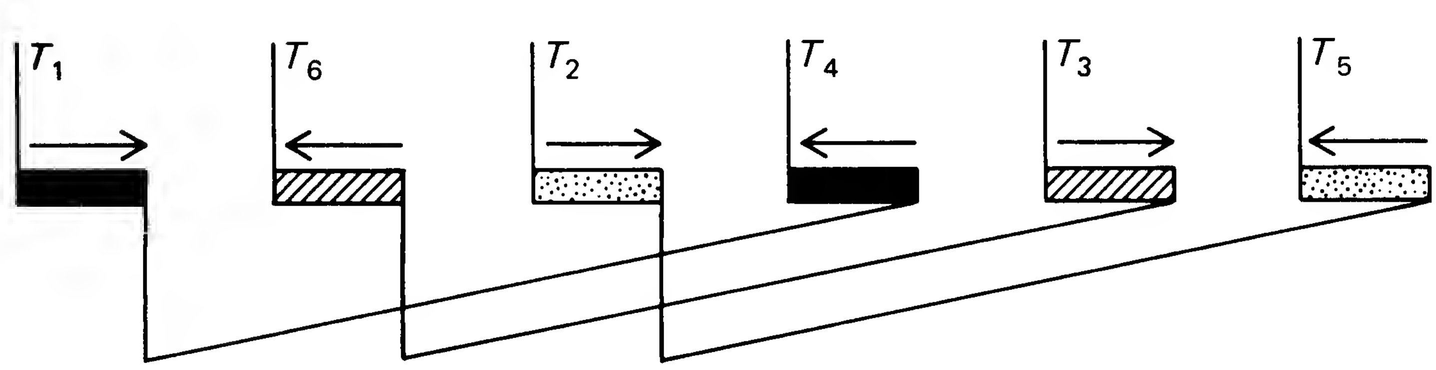


Fig. 3-91c. A two-pole, dual-voltage, wye-delta motor.

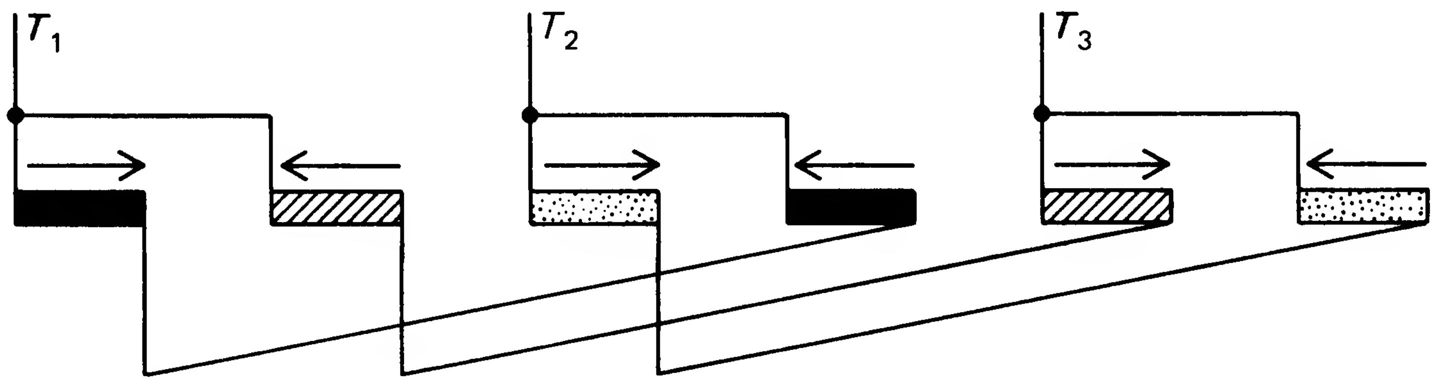


Fig. 3-91d. A two-pole, one-delta motor.

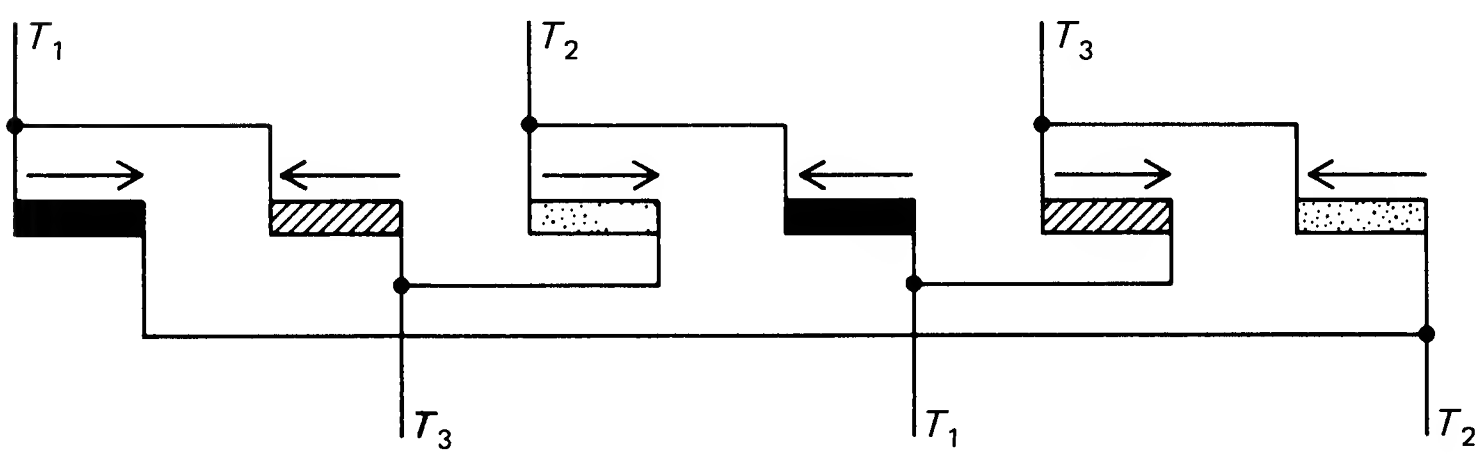


Fig. 3-91e. A two-pole, two-delta motor. Both T_1 leads can be brought out of the motor on one lead, as can the T_2 and T_3 leads.

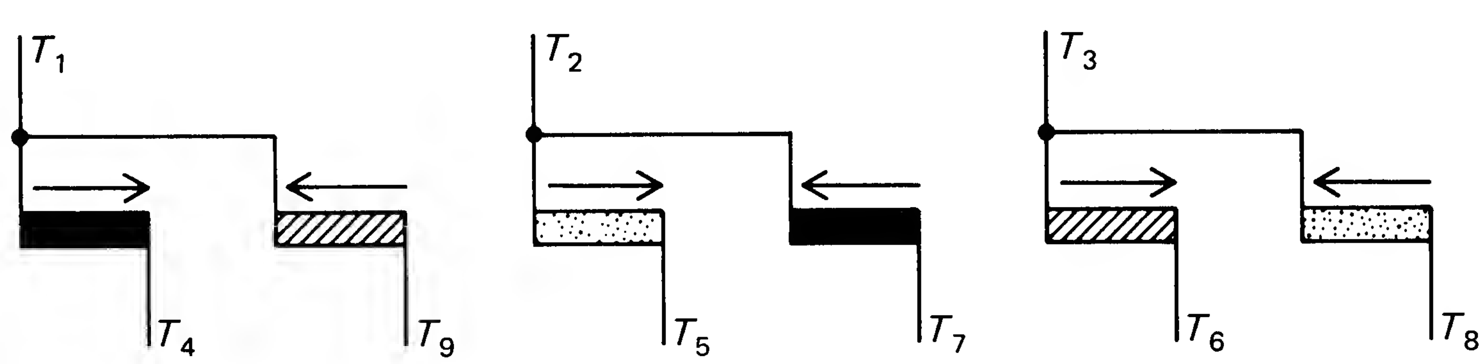


Fig. 3-91f. A two-pole, one- and two-delta motor.

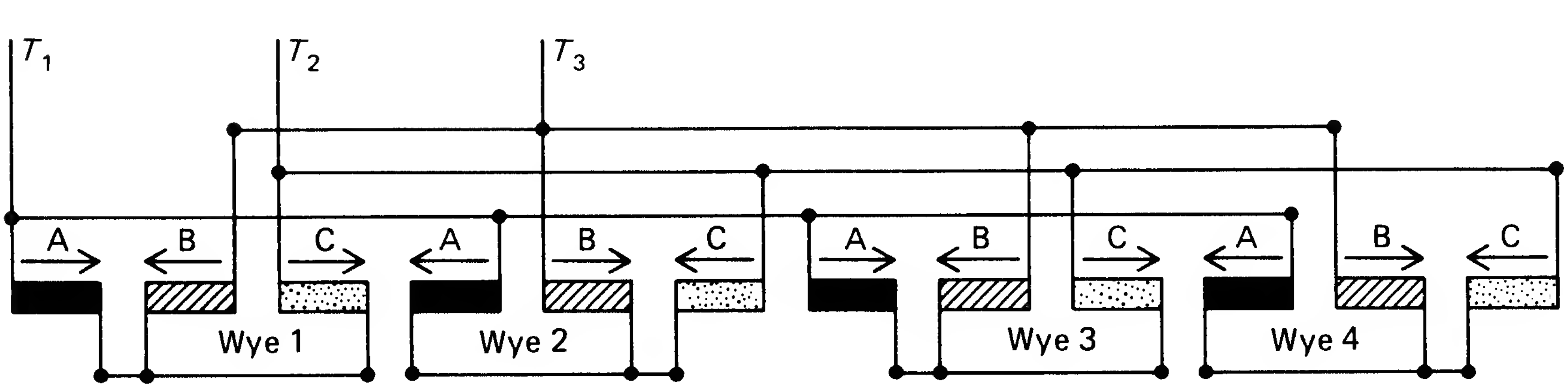


Fig. 3-92a. A four-pole, four-wye connection.

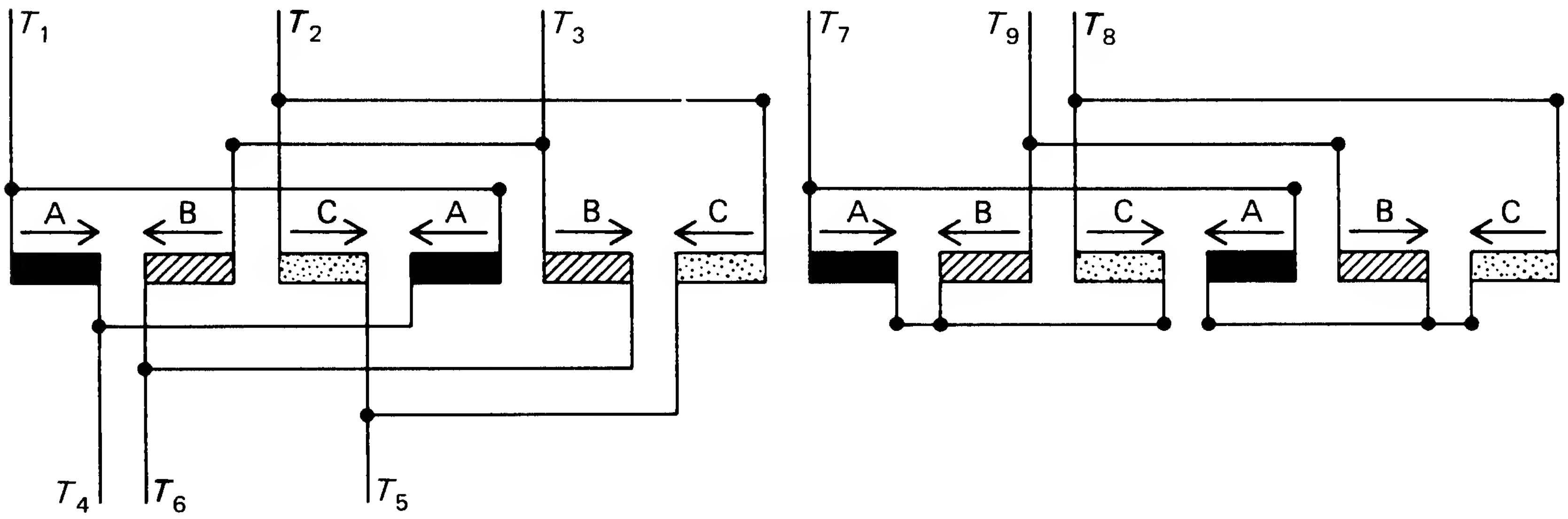


Fig. 3–92b. A four-pole, two- and four-wye, short jumper connection.

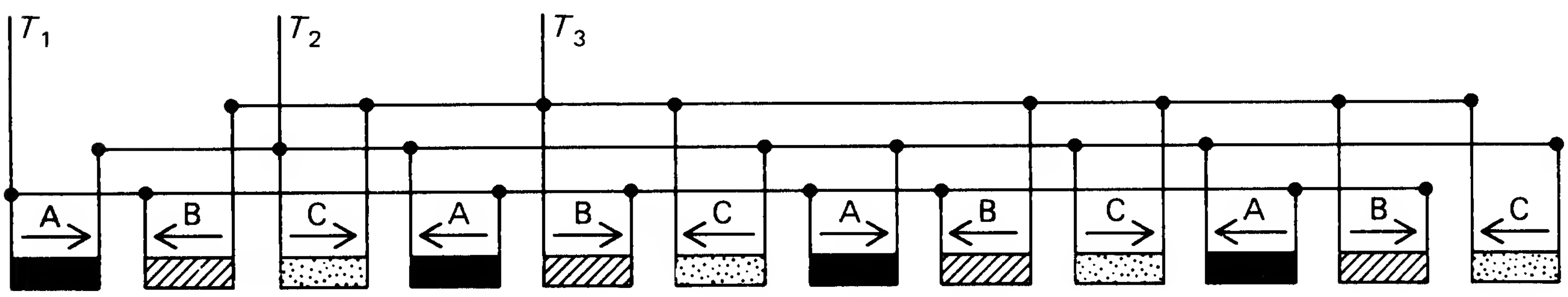


Fig. 3–92c. A four-pole, four-delta connection.

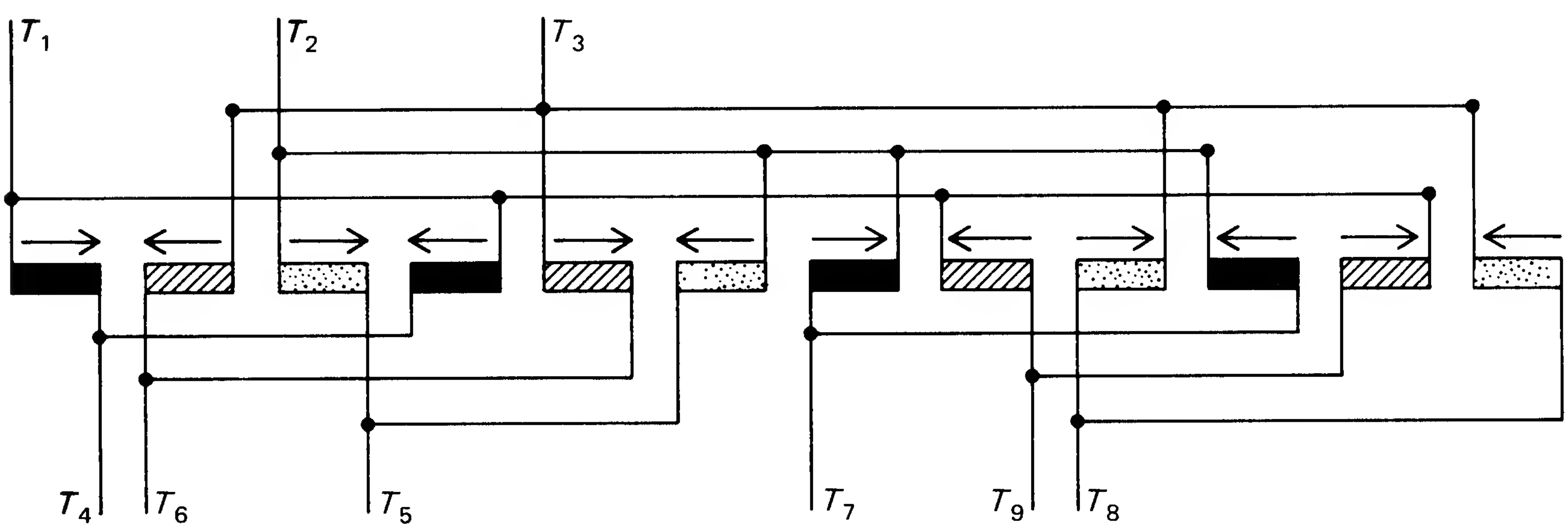


Fig. 3–92d. A four-pole, two- and four-delta, short jumper connection.

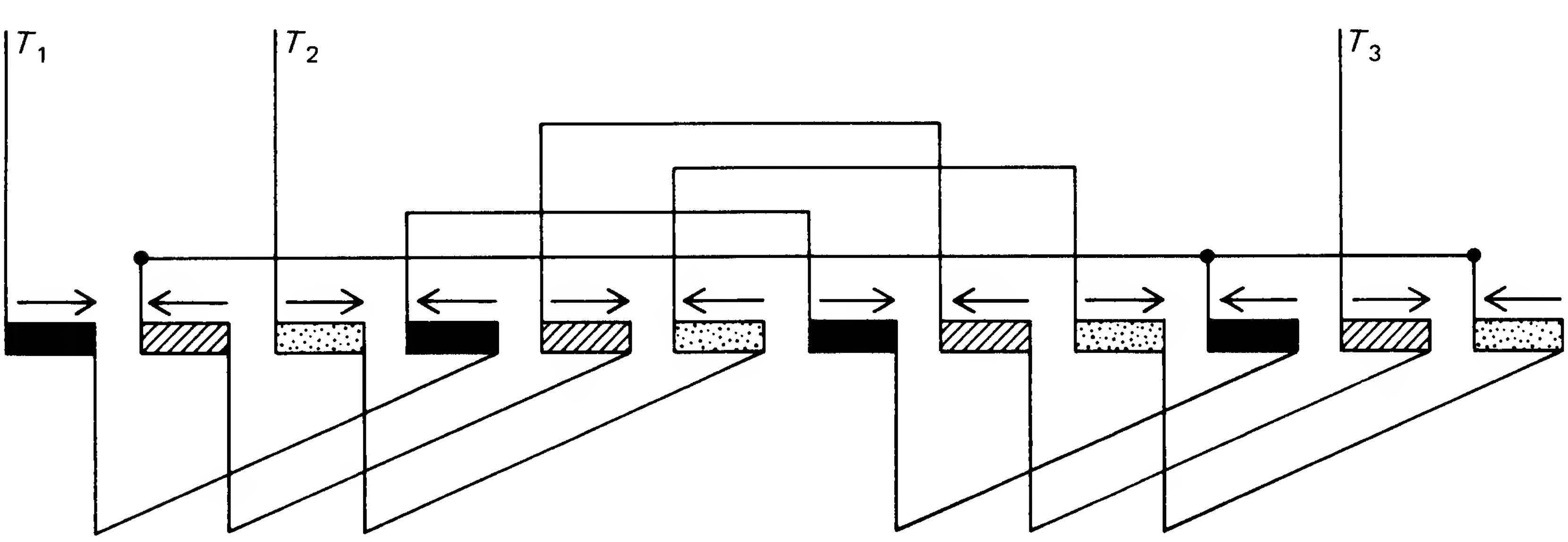


Fig. 3–92e. A four-pole, short jumper connection with the *B* phase connection starting at the opposite end, thereby reversing its polarity with respect to the *A* and *C* phases.

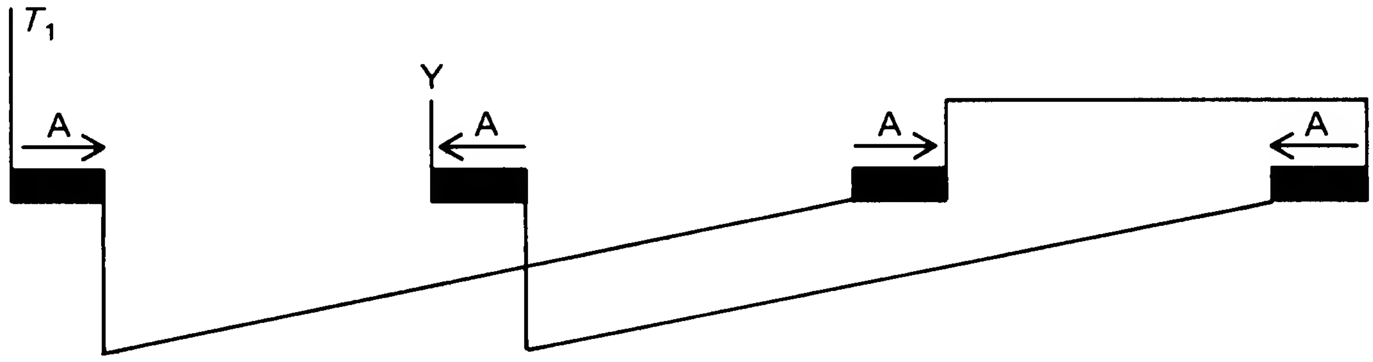


Fig. 3–93a. Phase *A* of a four-pole, one-wye, long jumper motor.

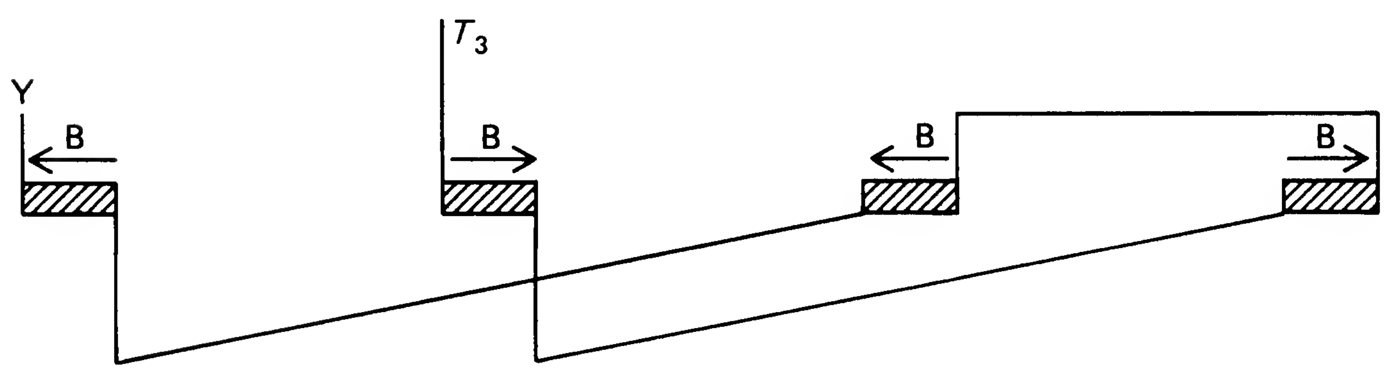


Fig. 3–93b. Phase *B* of a four-pole, one-wye, long jumper motor.

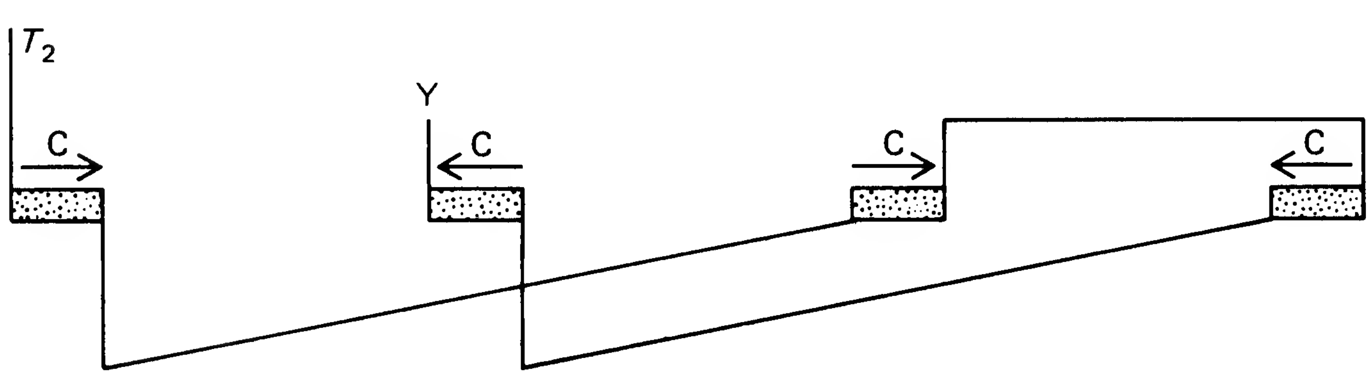


Fig. 3–93c. Phase *C* of a four-pole, one-wye, long jumper motor.

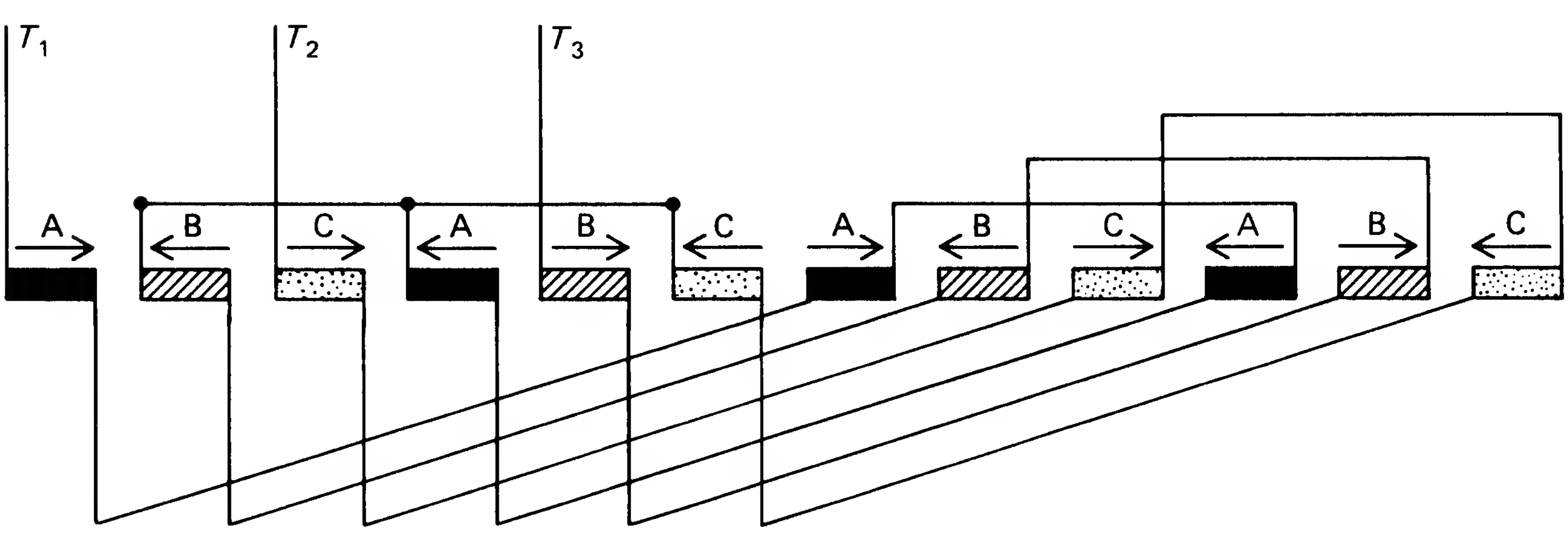


Fig. 3–94. A four-pole, one-wye, long jumper connection.

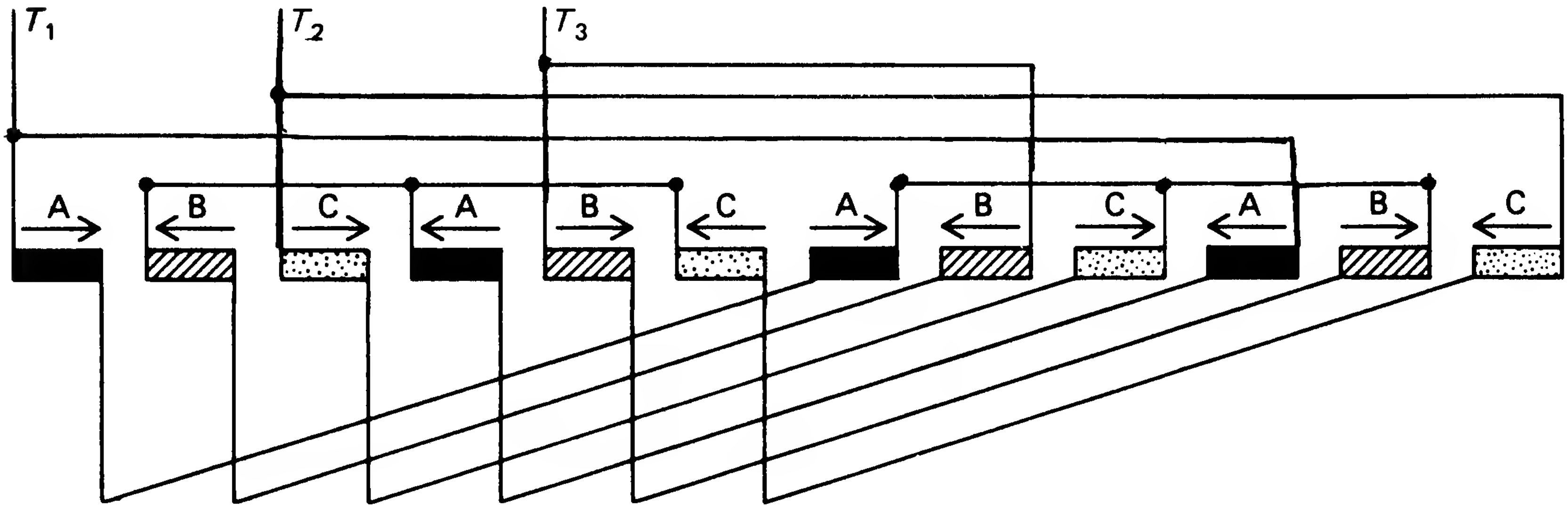


Fig. 3–95a. A four-pole, two-wye, long jumper connection.

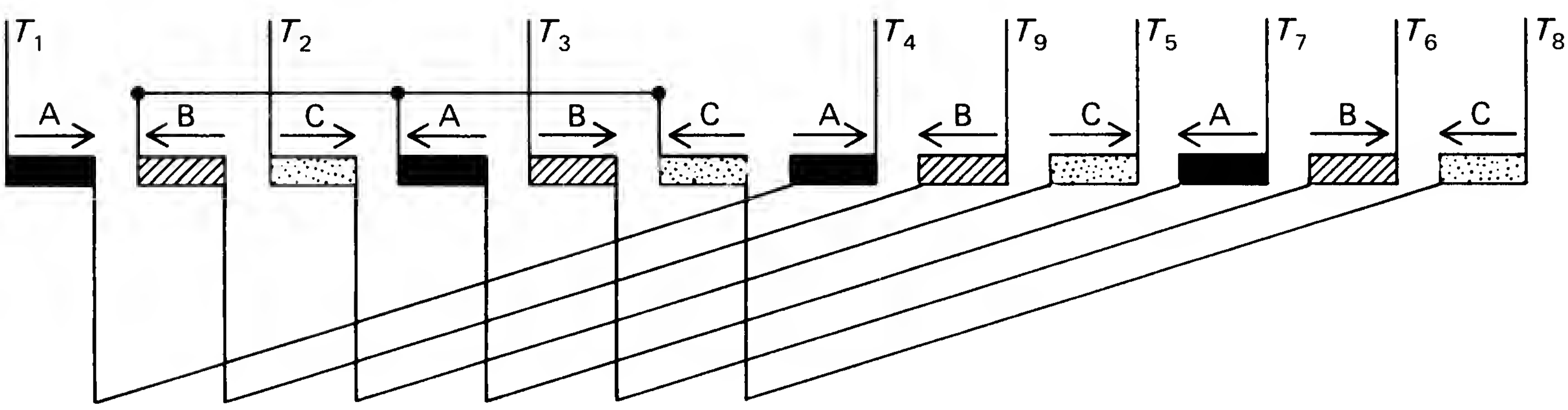


Fig. 3–95b. A four-pole, one- and two-wye, long jumper connection.

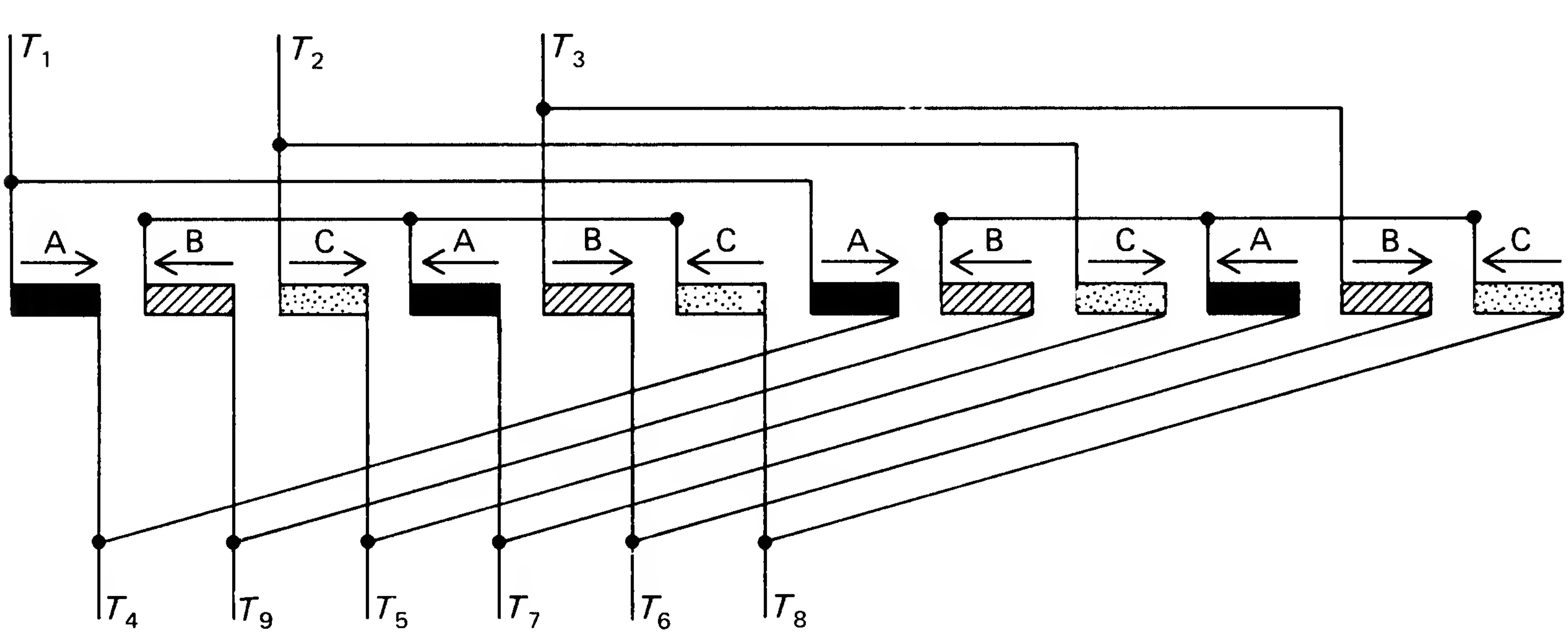


Fig. 3–95c. A four-pole, two- and four-wye, long jumper connection.

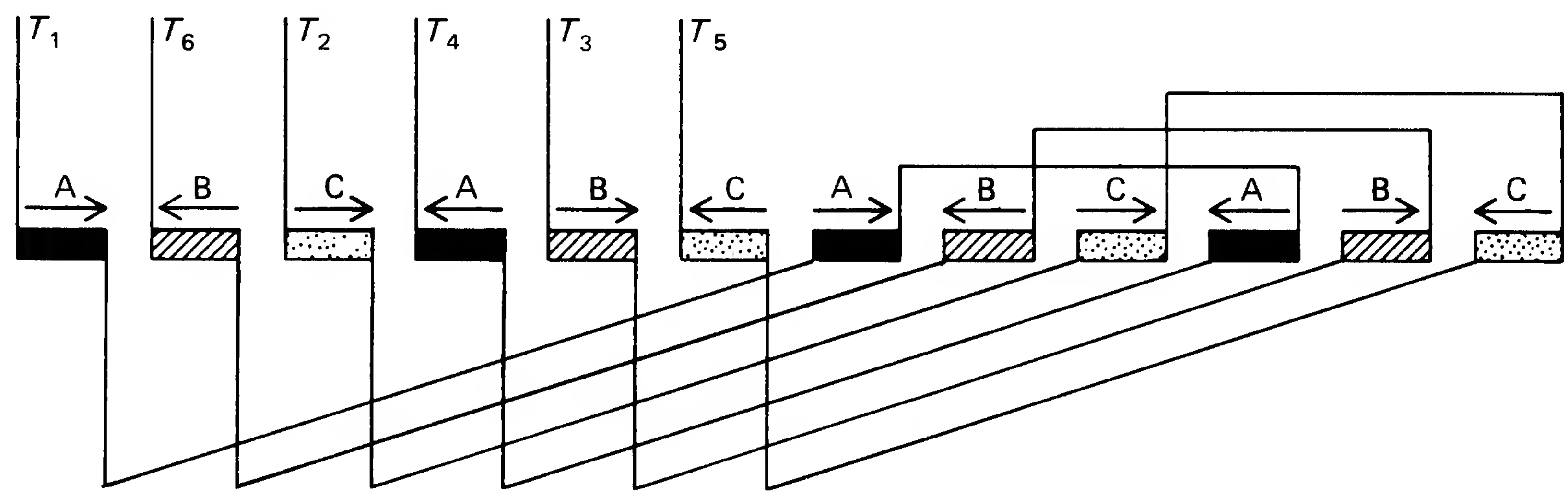


Fig. 3–95d. A four-pole, wye-delta, long jumper connection.

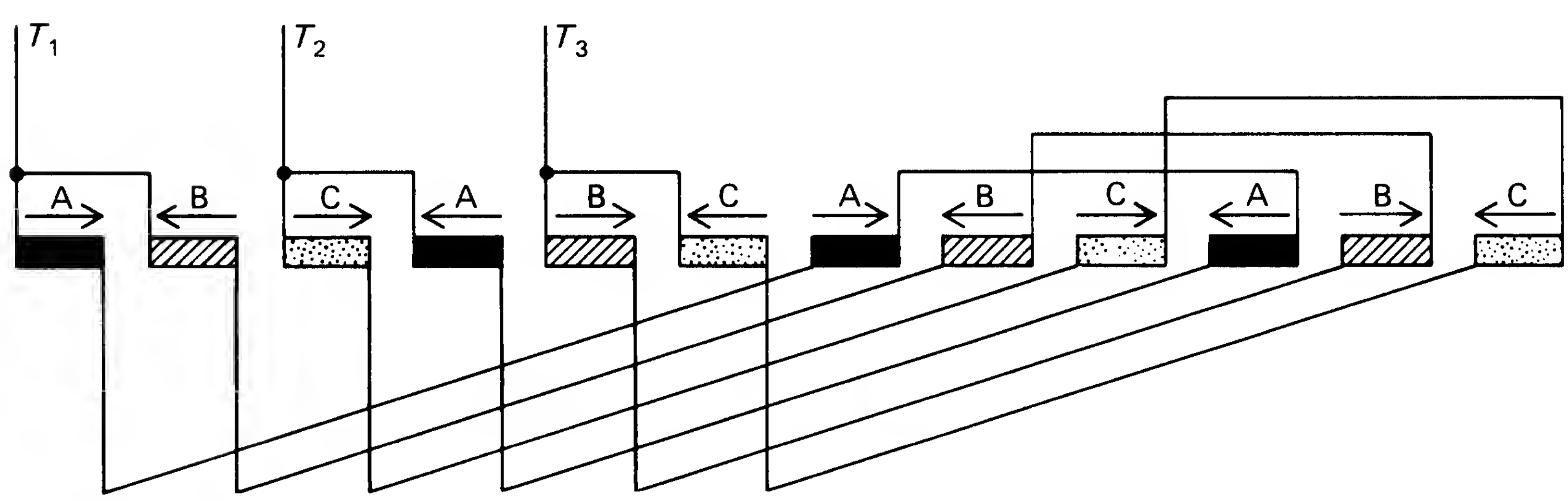


Fig. 3–96a. A four-pole, one-delta, long jumper connection.

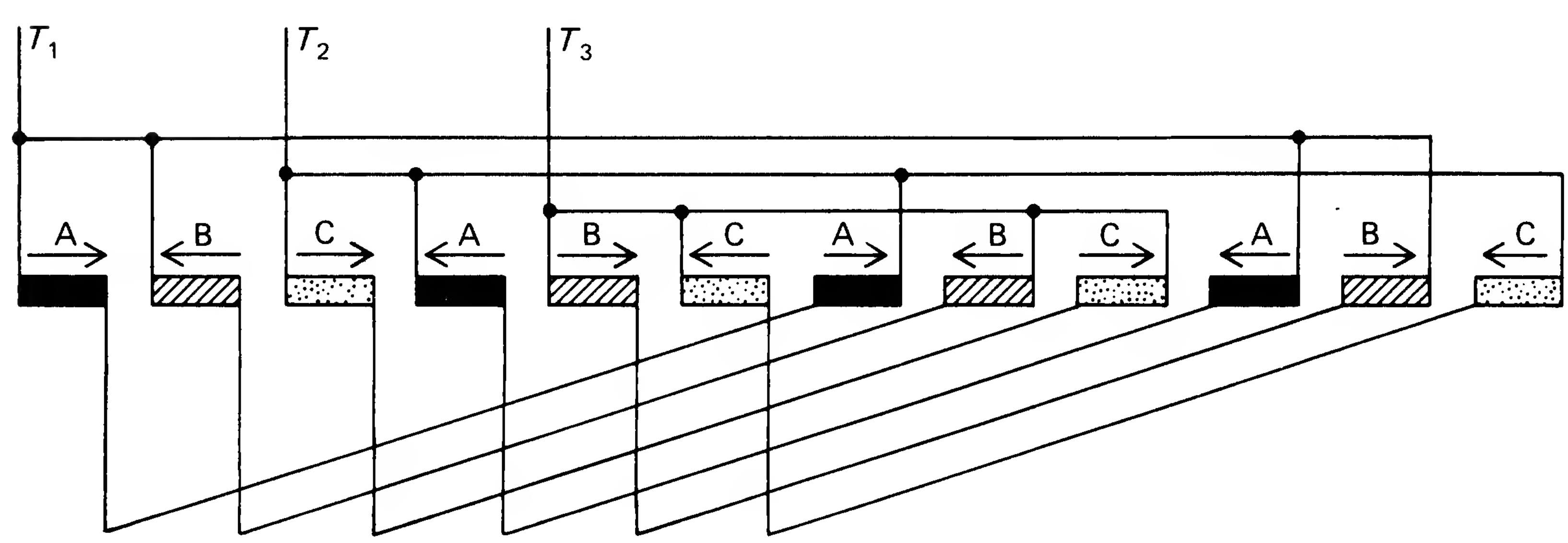


Fig. 3–96b. A four-pole, two-delta, long jumper connection.

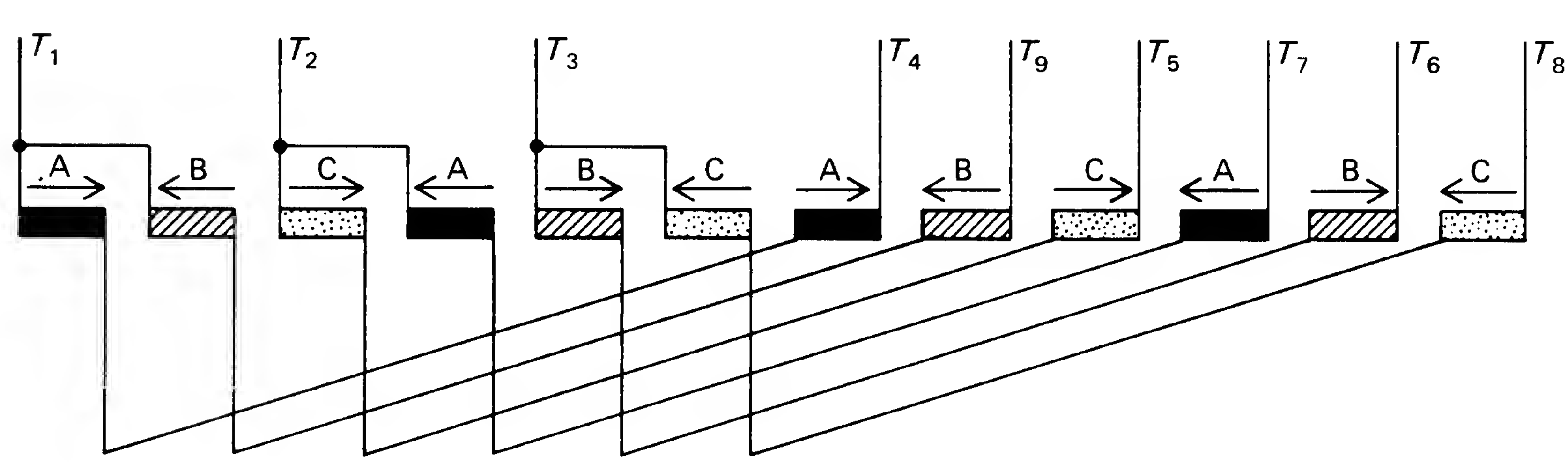


Fig. 3–96c. A four-pole, one- and two-delta, long jumper connection.

Figures 3–95d; 3–96a; 3–96b; 3–96c

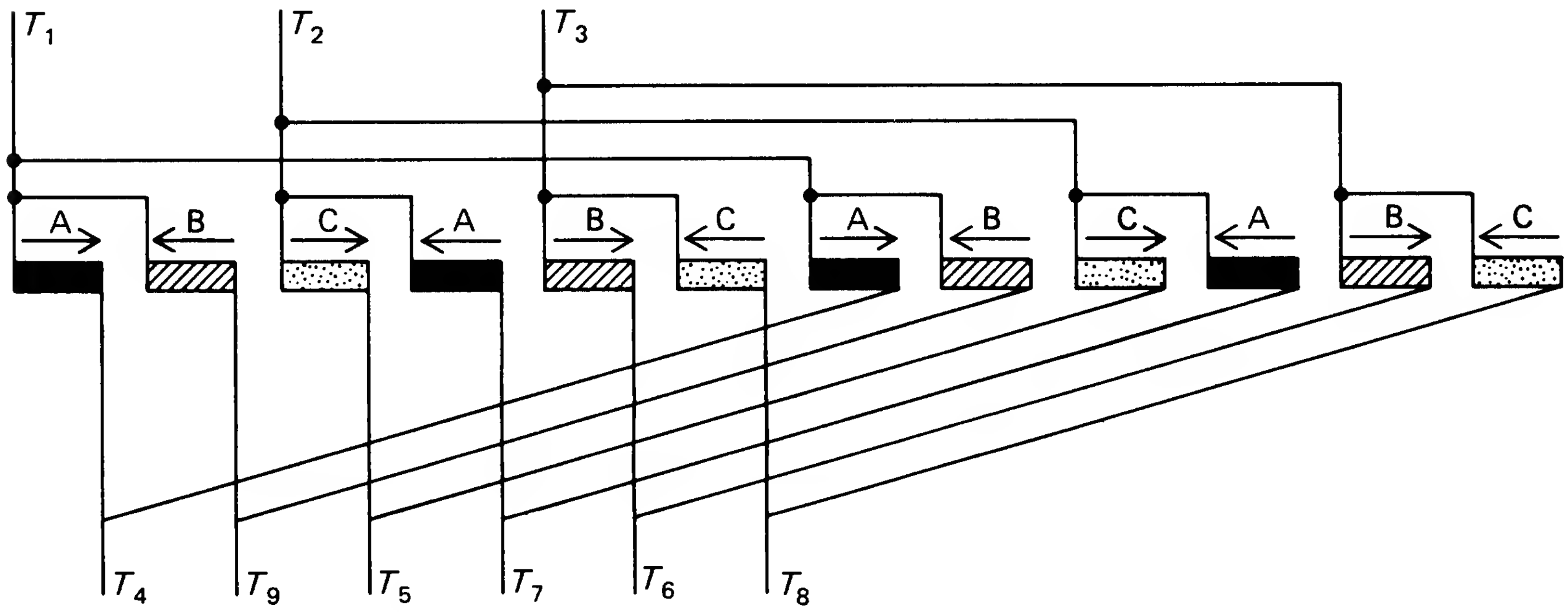


Fig. 3–96d. A four-pole, two- and four-delta, long jumper connection.

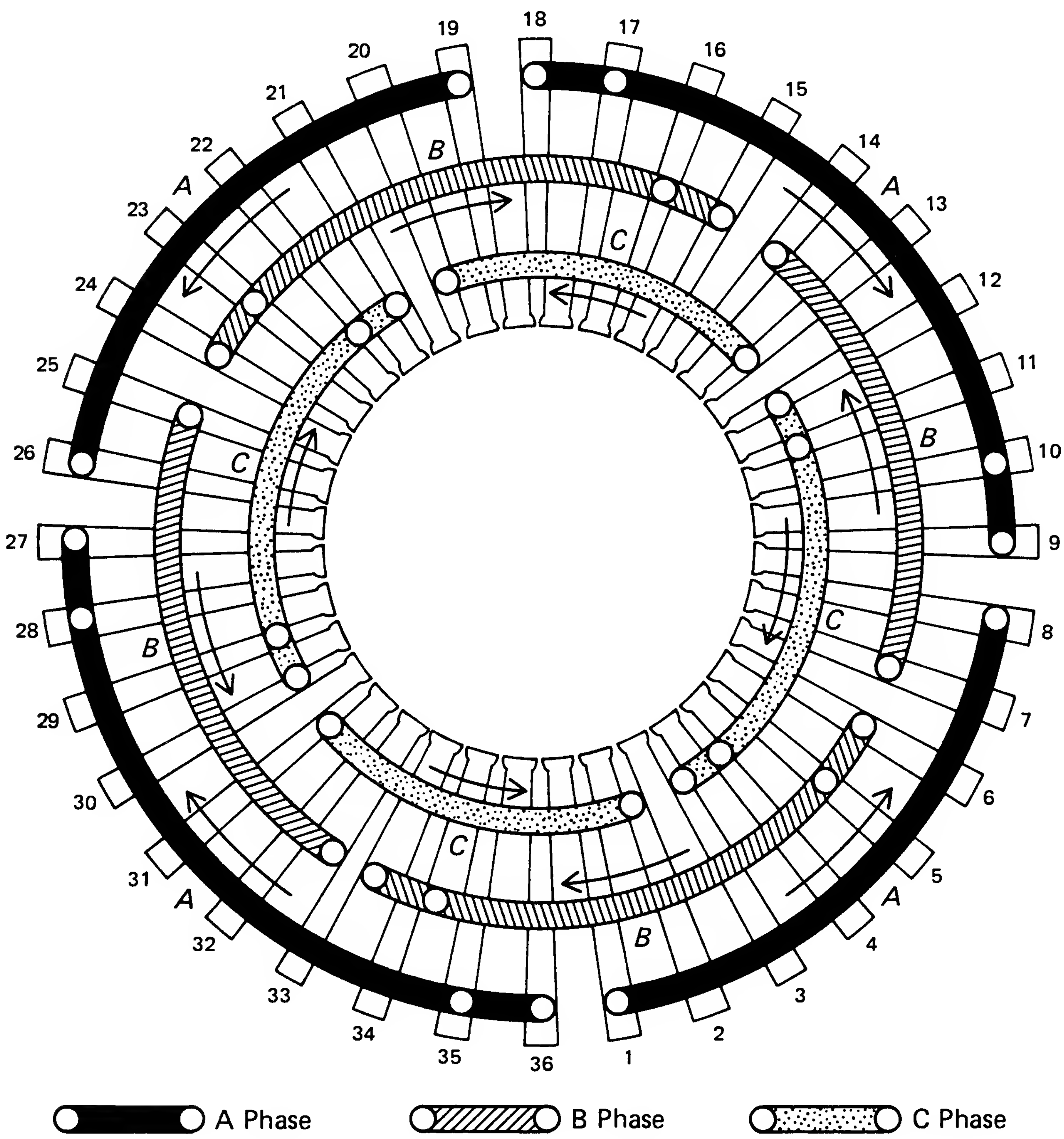


Fig. 3–97. A circular diagram of a three-layer concentric winding with coil groups containing one and two coils per group. Each layer is a complete phase and is shown as it would be placed in a stator.

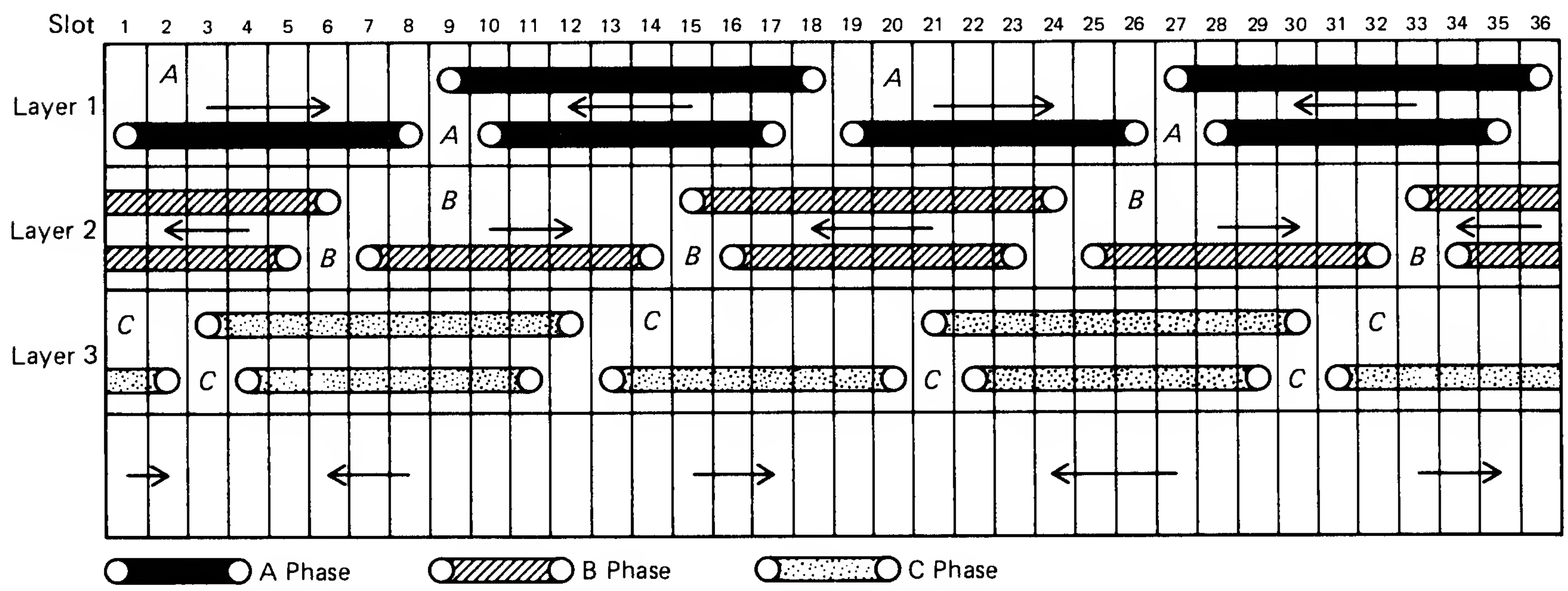


Fig. 3-98. A straight-line diagram of the motor illustrated in **Fig. 3-97.** This is a three-layer concentric winding, with each layer containing a complete phase.

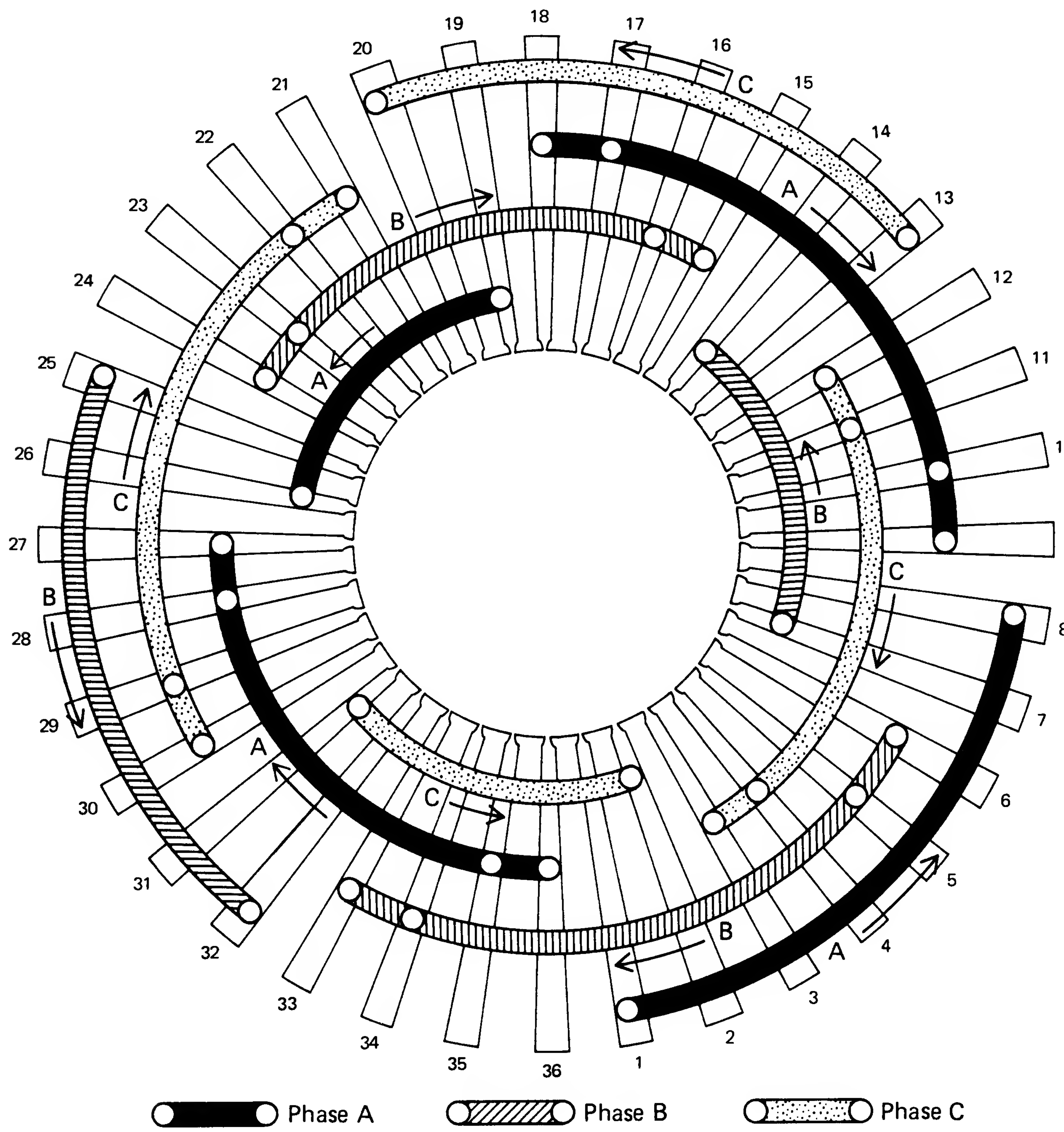


Fig. 3-99. A circular diagram of a four-layer concentric winding with coil groups containing one and two coils per group. This motor can be rewound with the same arrangement as in **Fig. 3-97** with little difference electrically.

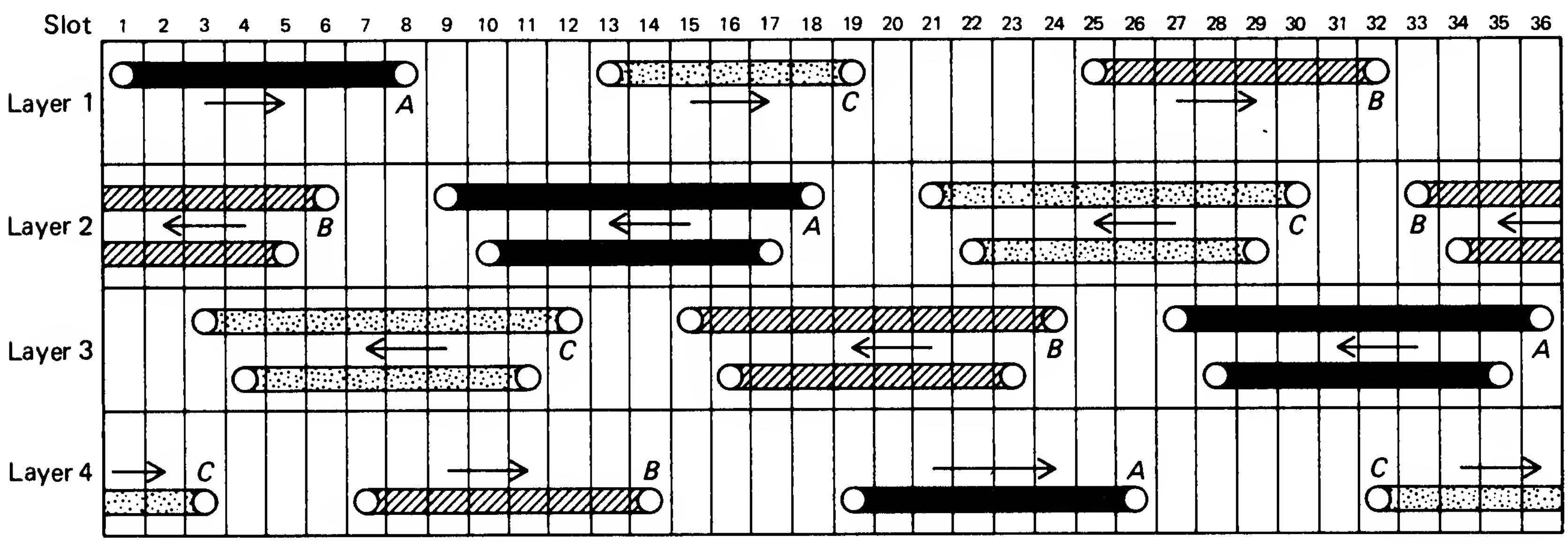


Fig. 3-100. A straight-line illustration of a four-layer winding, as shown in Fig. 3-99. The first and fourth layer have one coil per group, and the second and third layer have two coils per group.

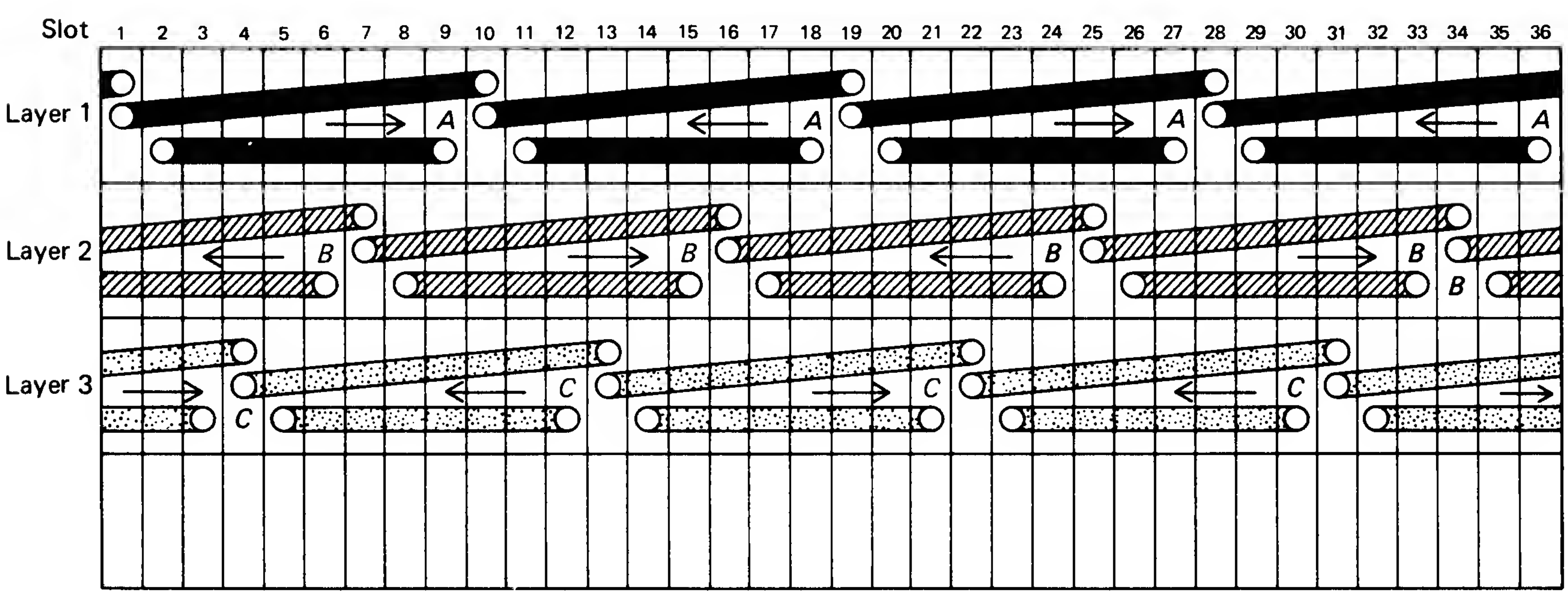


Fig. 3-101. A four-pole concentric winding with two coils per group. The outside coils of each group share the slot.

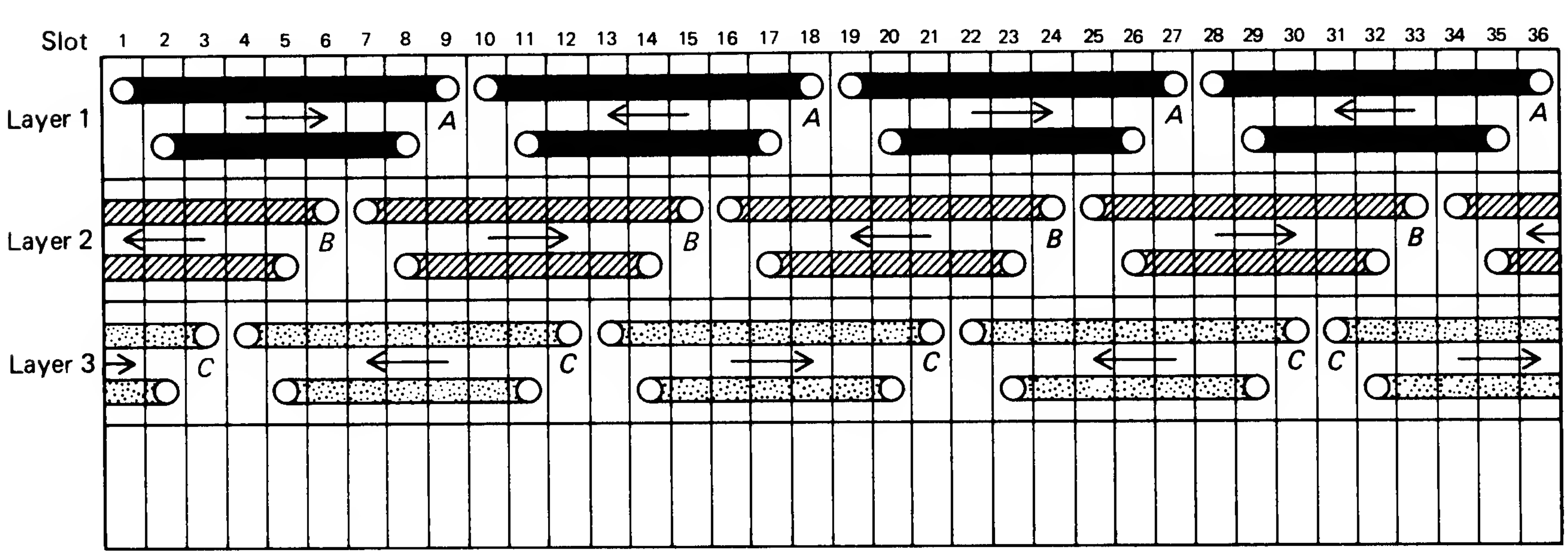


Fig. 3-102. A four-pole concentric winding with each group containing two coils. The inside coils of each group share the slot.

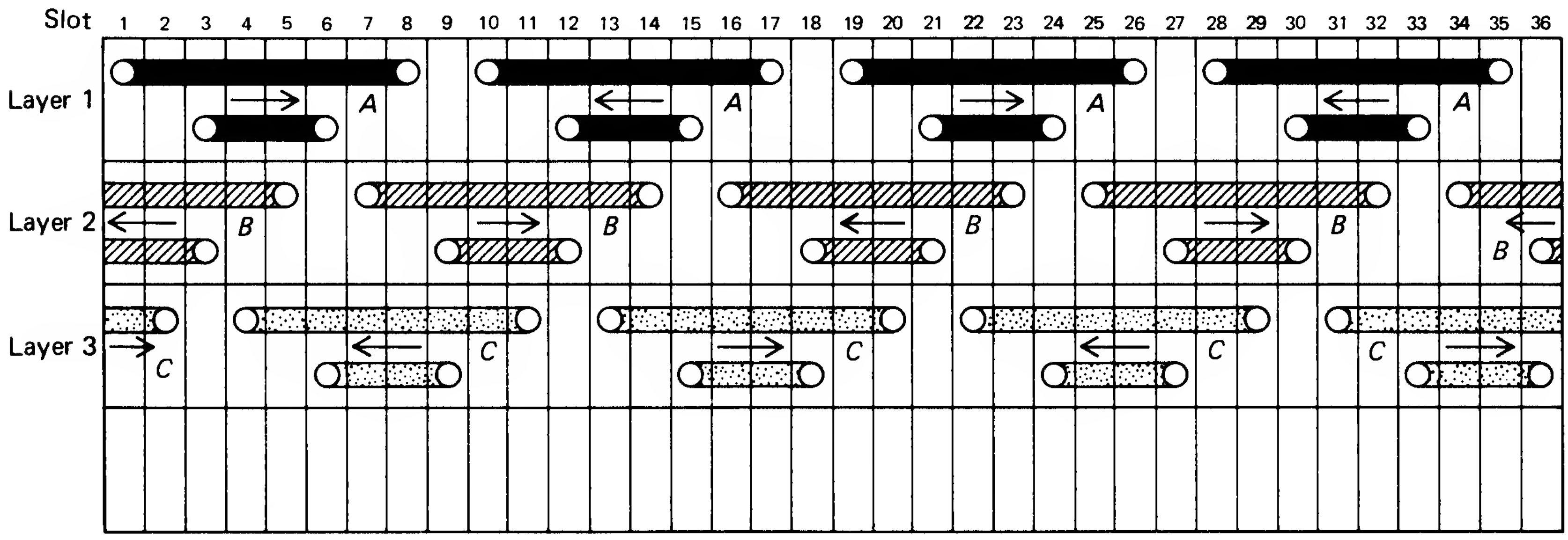


Fig. 3-103. A four-pole, concentric winding with two coils per group. This pattern has an empty slot on each side of the outer coil of each group. The inside coils share the slot.

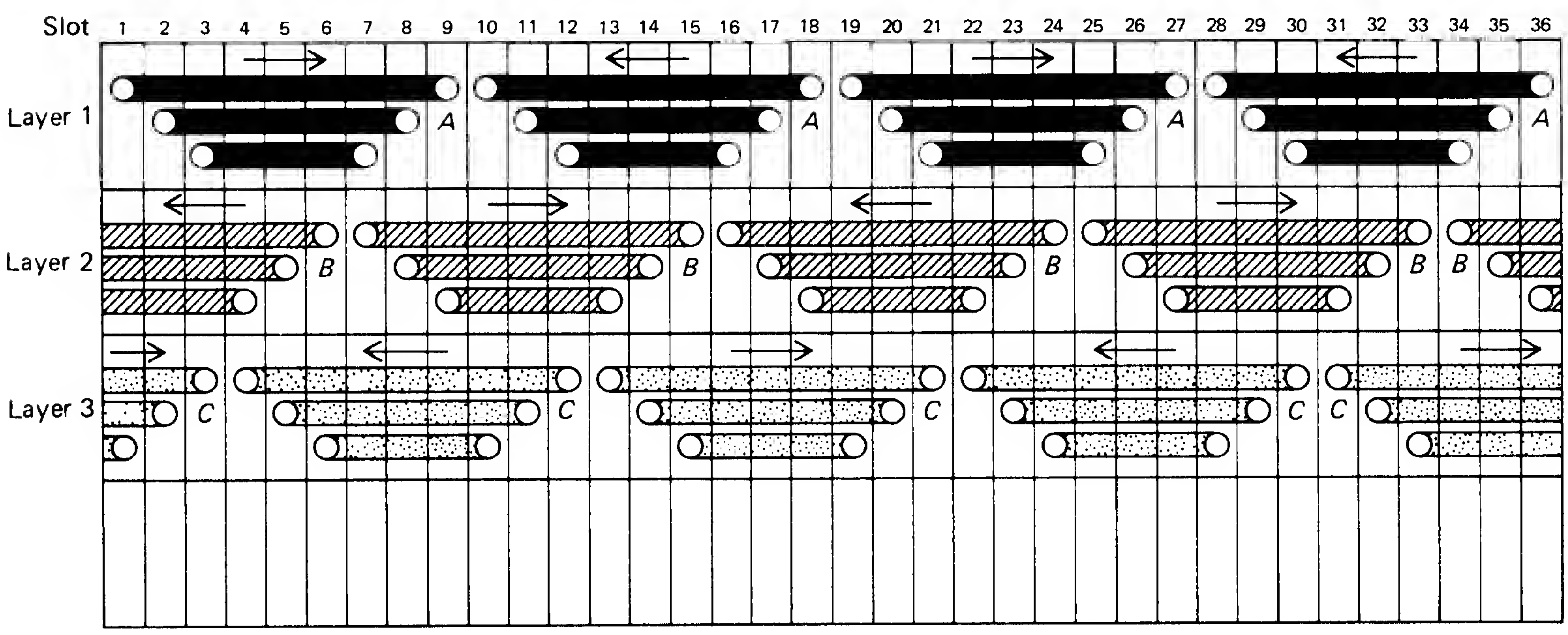


Fig. 3-104. A four-pole, concentric winding with three coils per group, all sharing the slot.

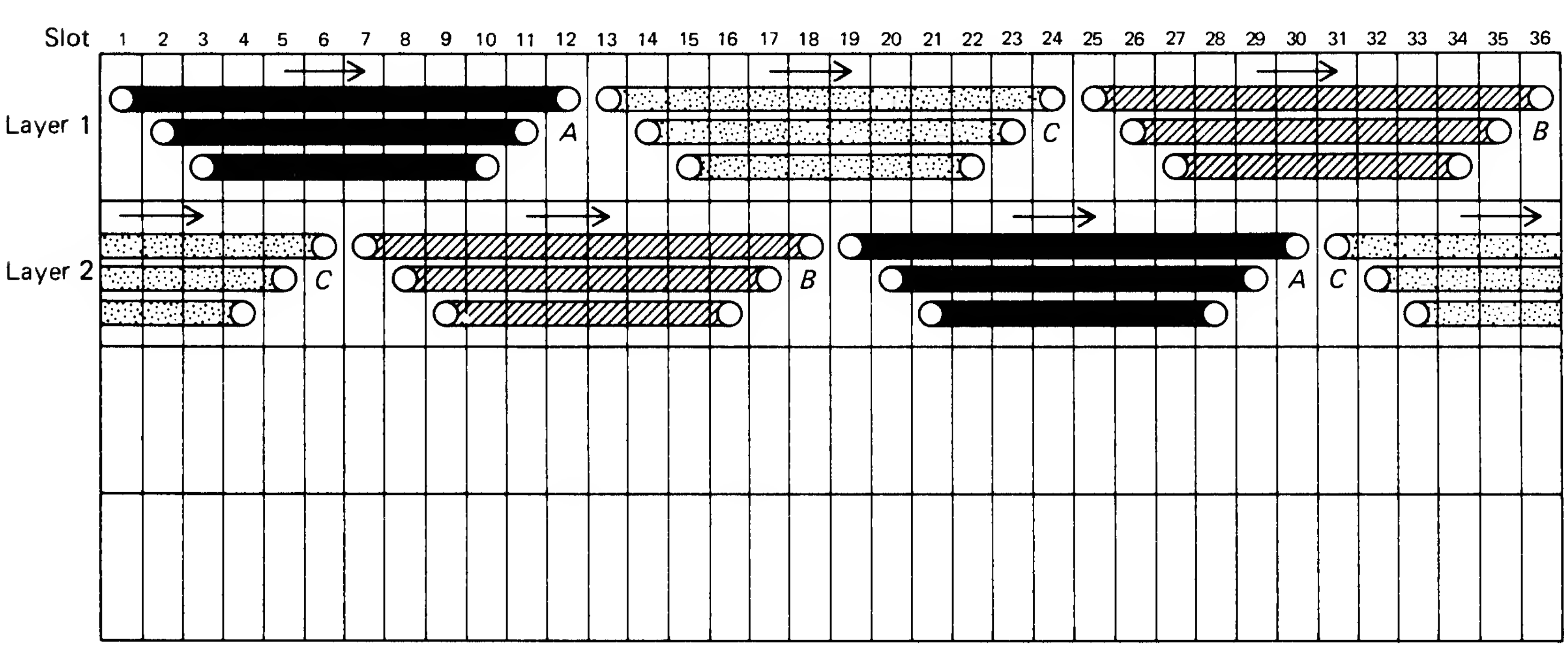


Fig. 3-105. A straight-line diagram of a four-pole, consequent-pole winding.

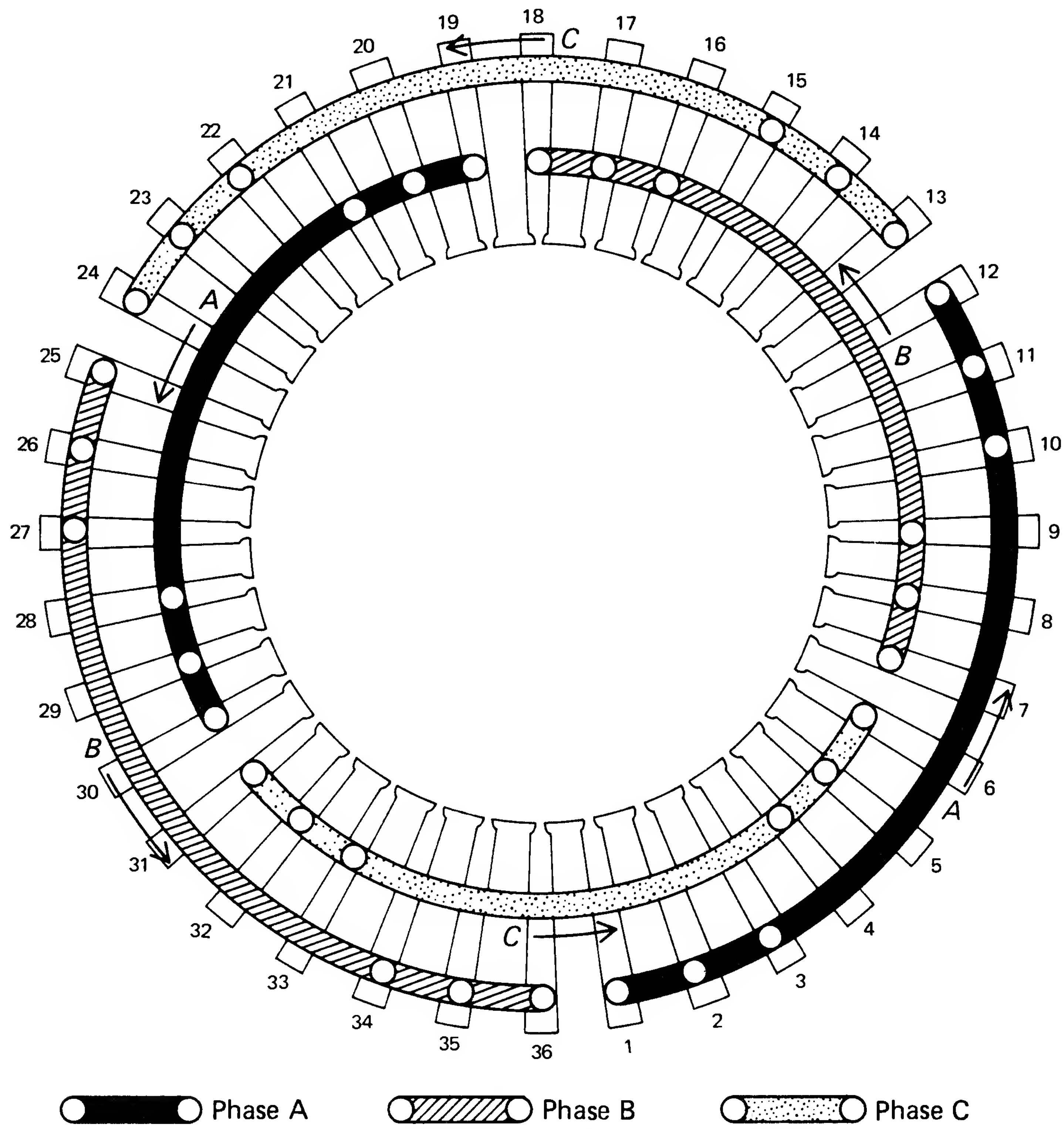


Fig. 3–106. A circular diagram of a six-coil group, four-pole, consequent pole winding, showing where the coils are placed in the stator.

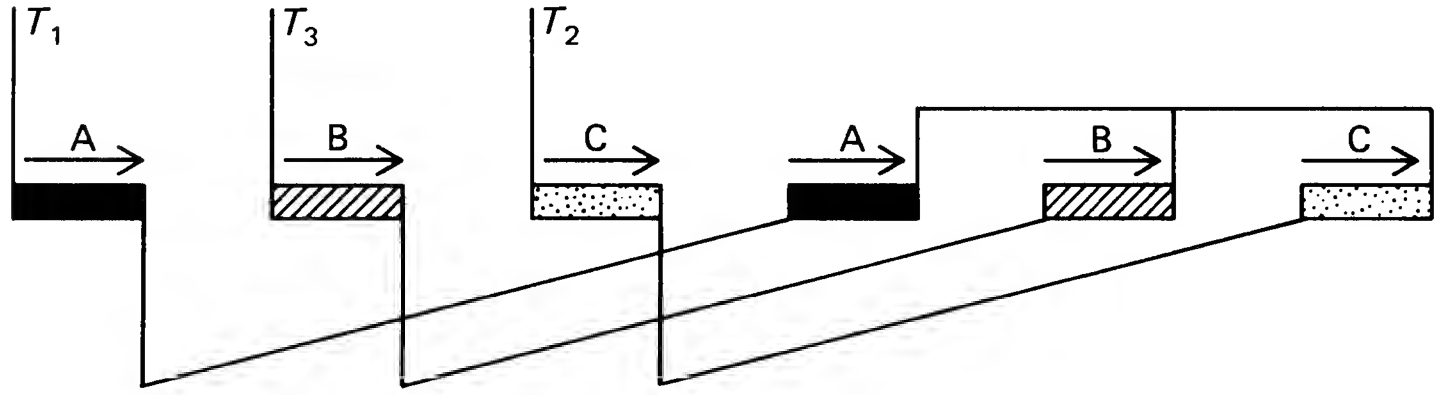


Fig. 3–107a. A four-pole, consequent-pole, one-wye connection.

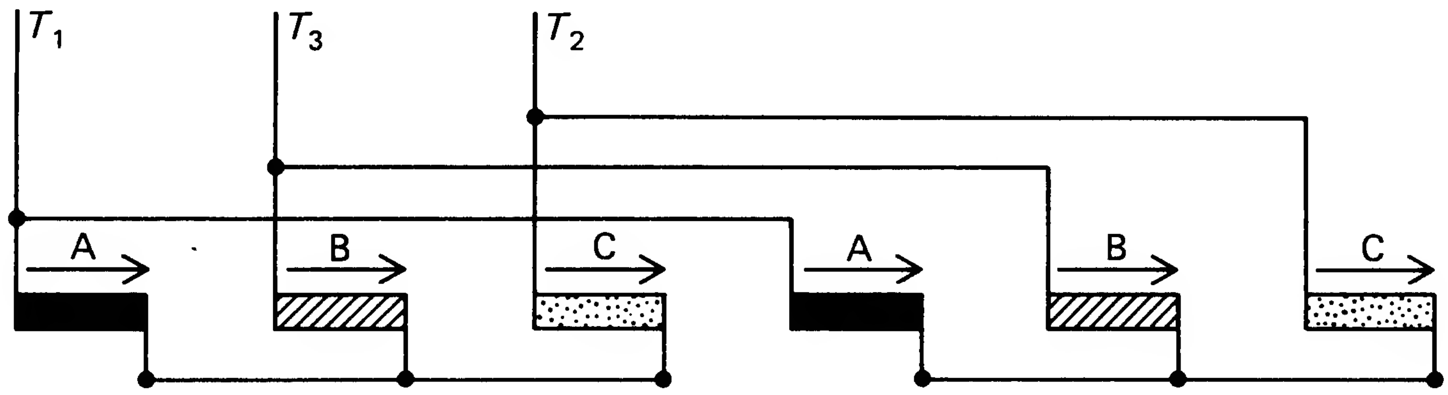


Fig. 3–107b. A four-pole, consequent-pole, two-wye connection.

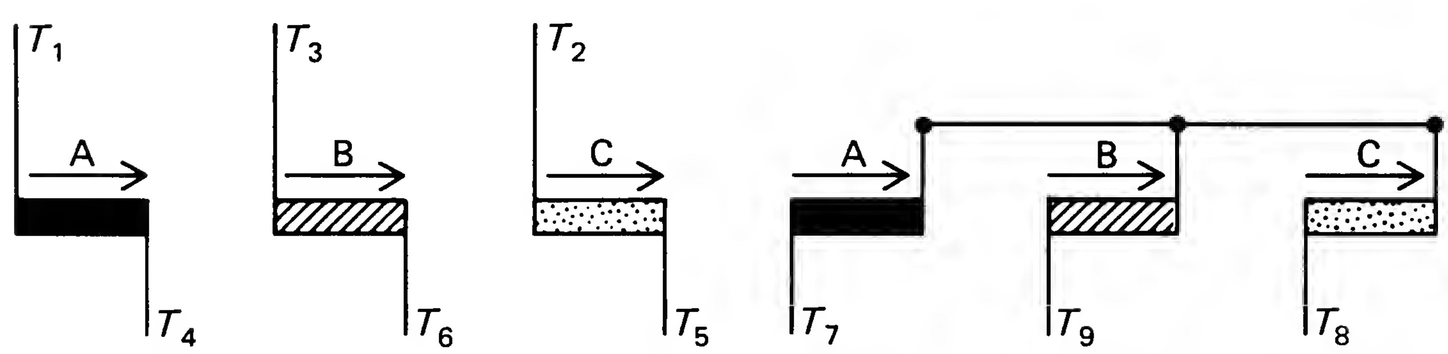


Fig. 3–107c. A four-pole, consequent-pole, one- and two-wye connection.

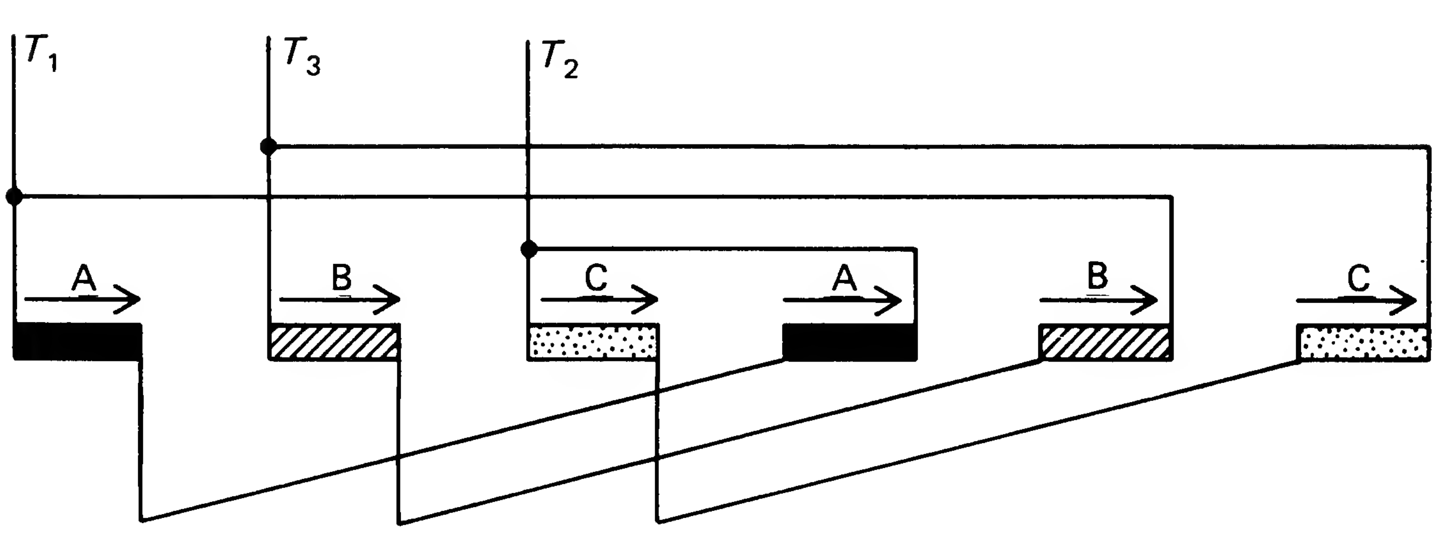


Fig. 3–107d. A four-pole, consequent-pole, one-delta connection.

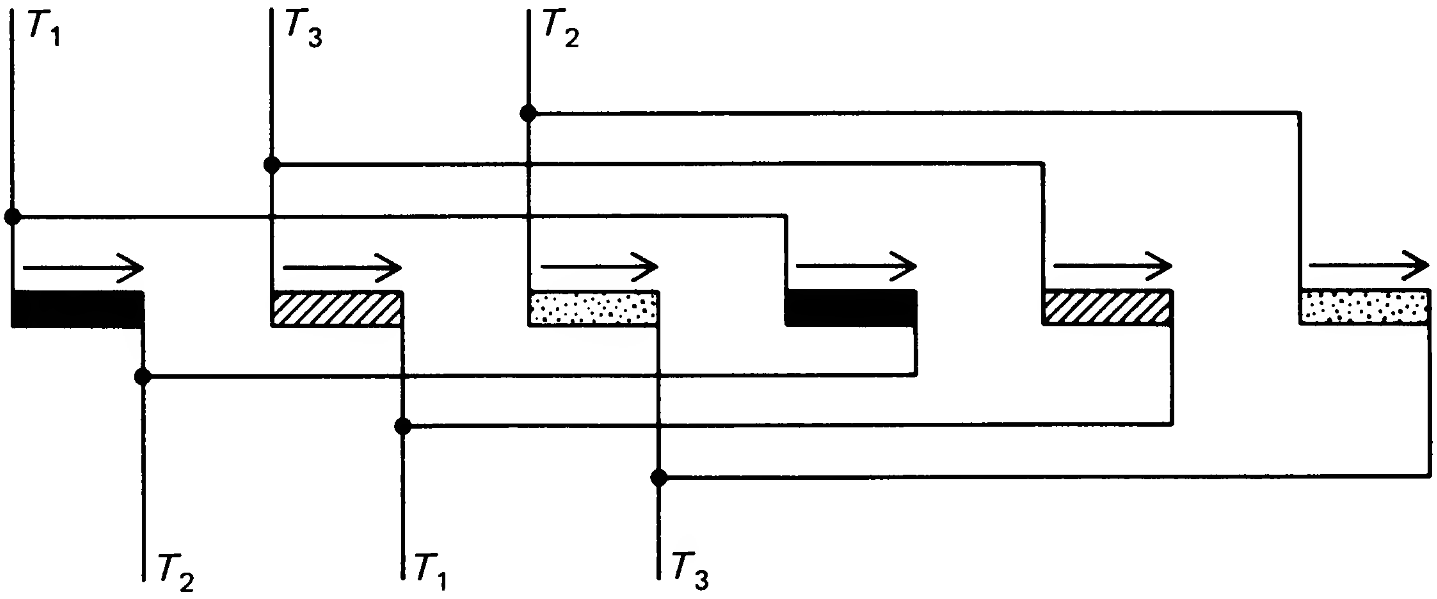


Fig. 3–107e. A four-pole, consequent-pole, two-delta connection. Like numbers are joined and brought out of the motor on one lead.

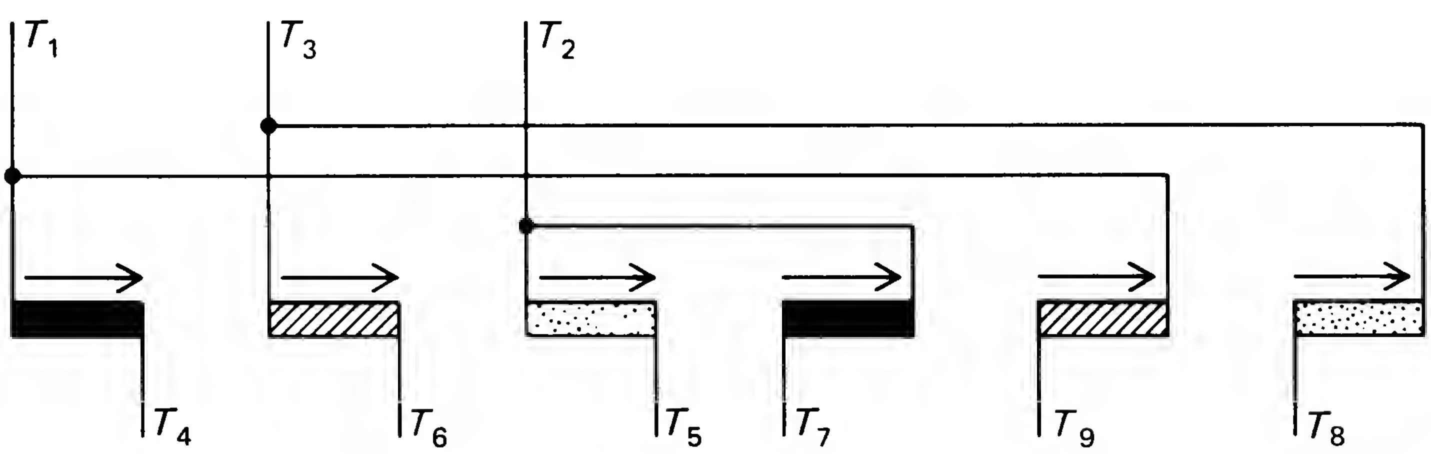


Fig. 3–107f. A four-pole, consequent-pole, one- and two-delta connection.

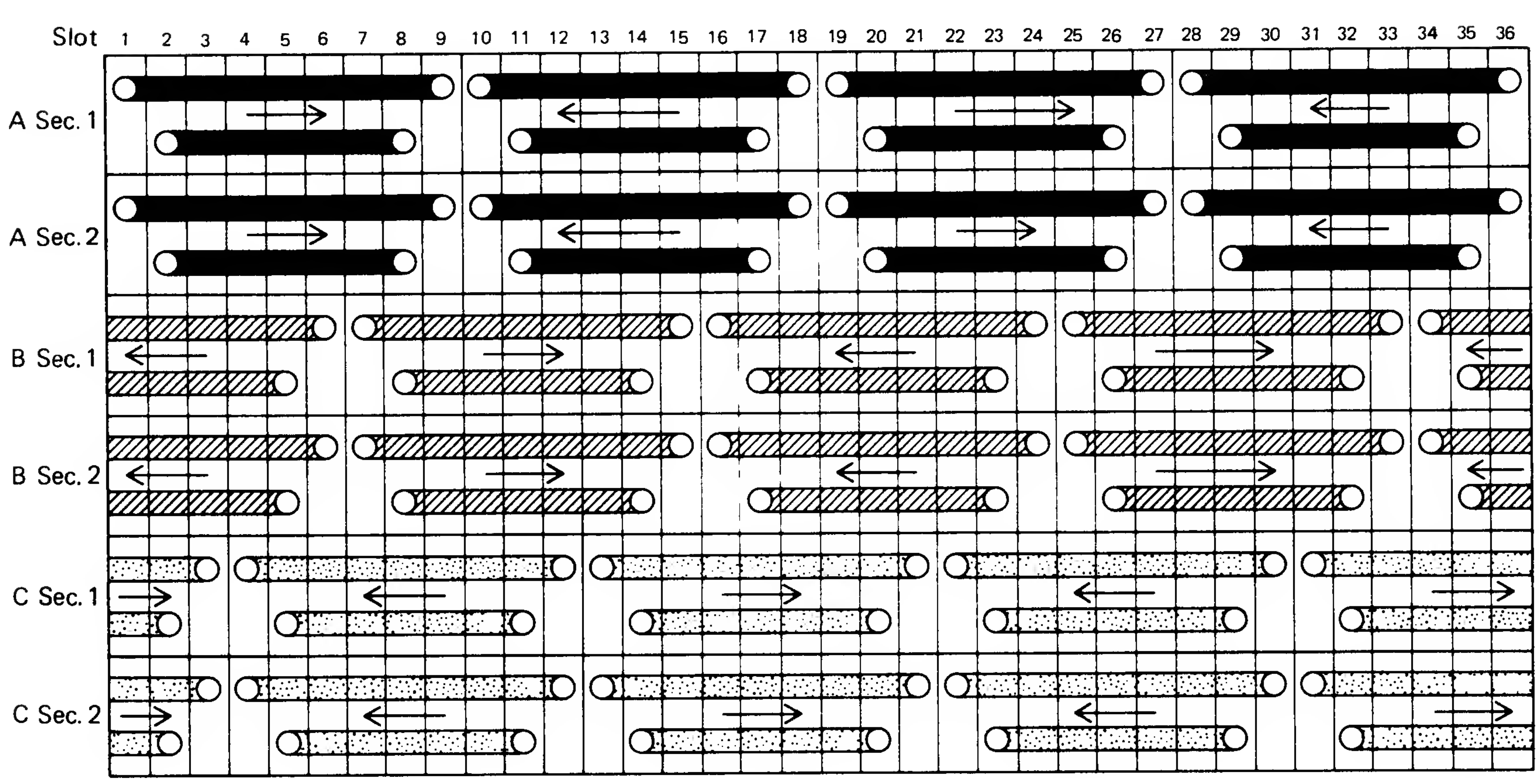


Fig. 3–108. A four-pole concentric winding with each group split into two sections. Each section is a circuit when connected, as in **Fig. 3–109.**

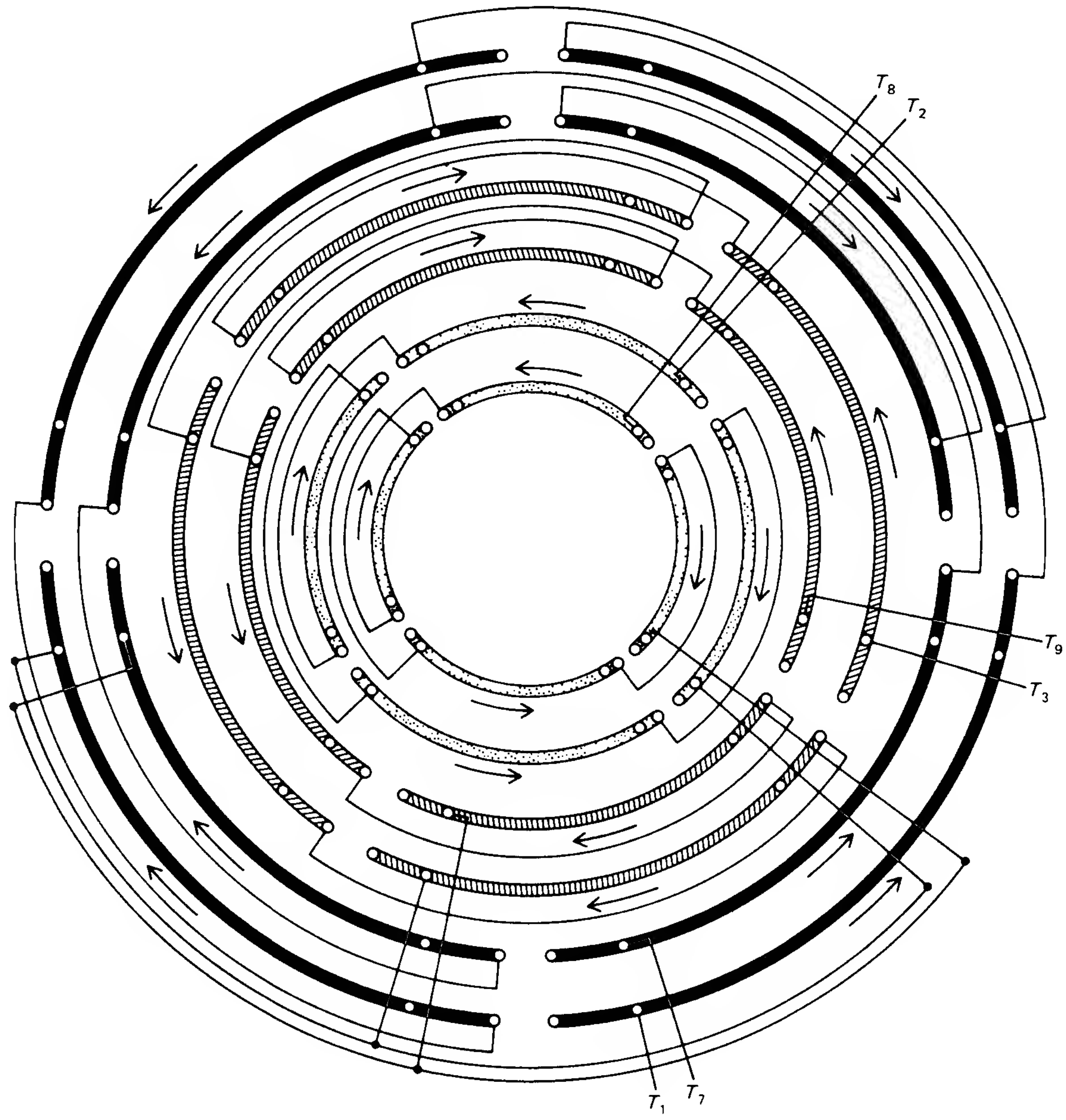


Fig. 3–109. A four-pole, concentric winding, with each coil group split into two sections. It is connected for a part-winding start and is two wye.

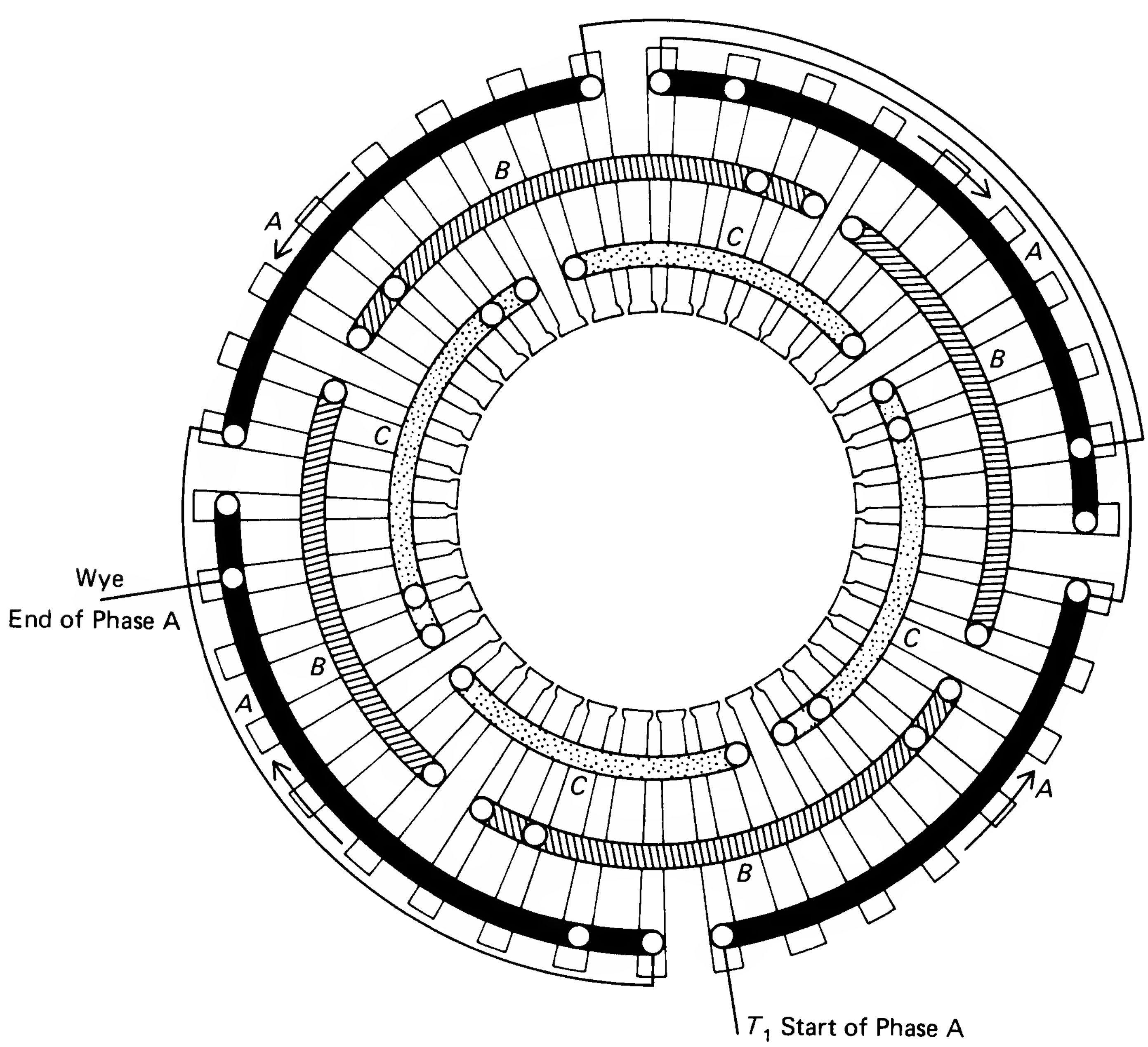


Fig. 3–110a. Phase *A* connections, starting at the six o'clock position and proceeding to the right in a counterclockwise direction.

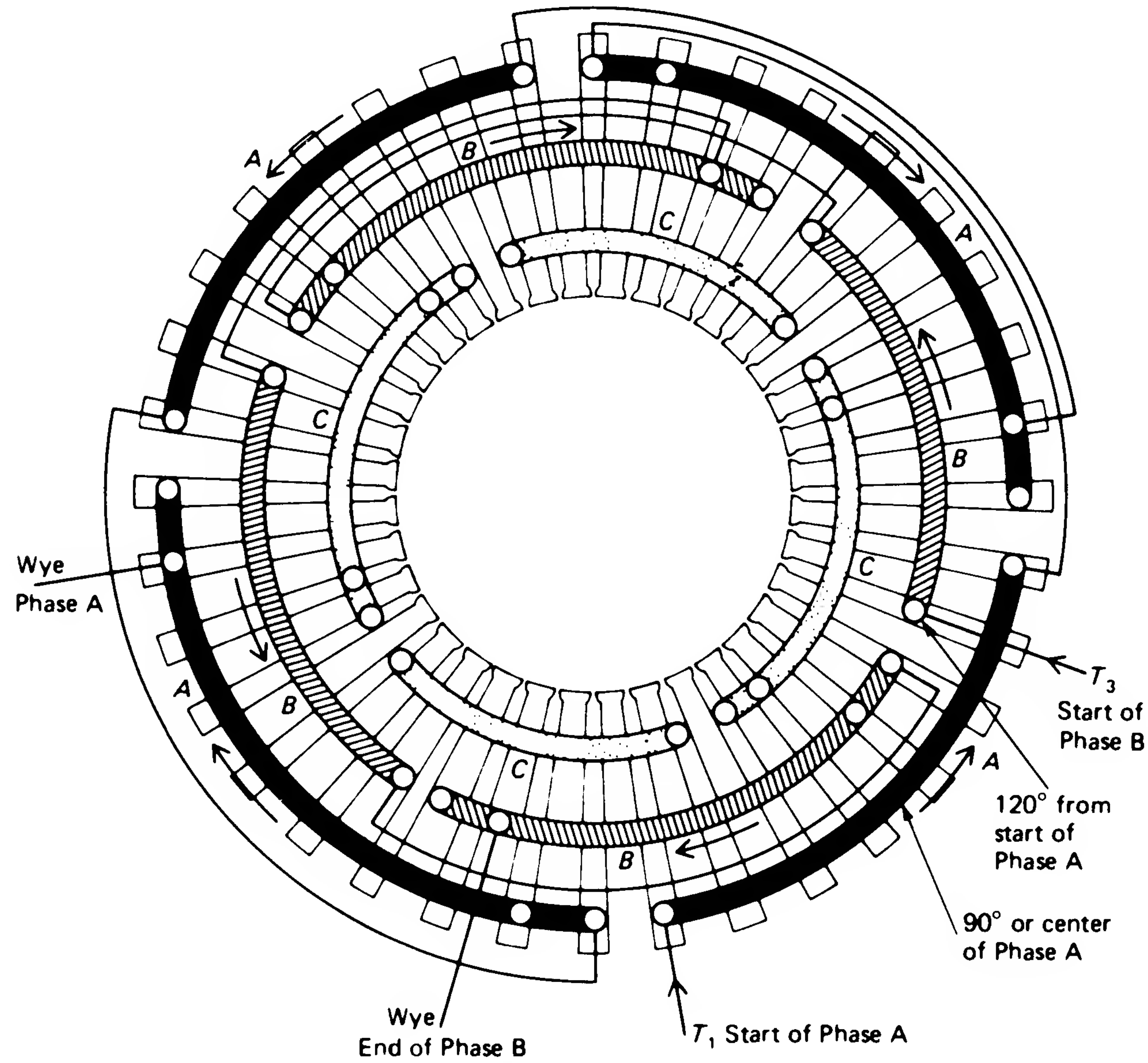


Fig. 3-110b. Start of the *B* phase at 120° to the right of the start of the *A* phase. This is the first coil located to the right of center or the 90° spot of the *A* phase and is connected at the same polarity as the first coil of the *A* phase.

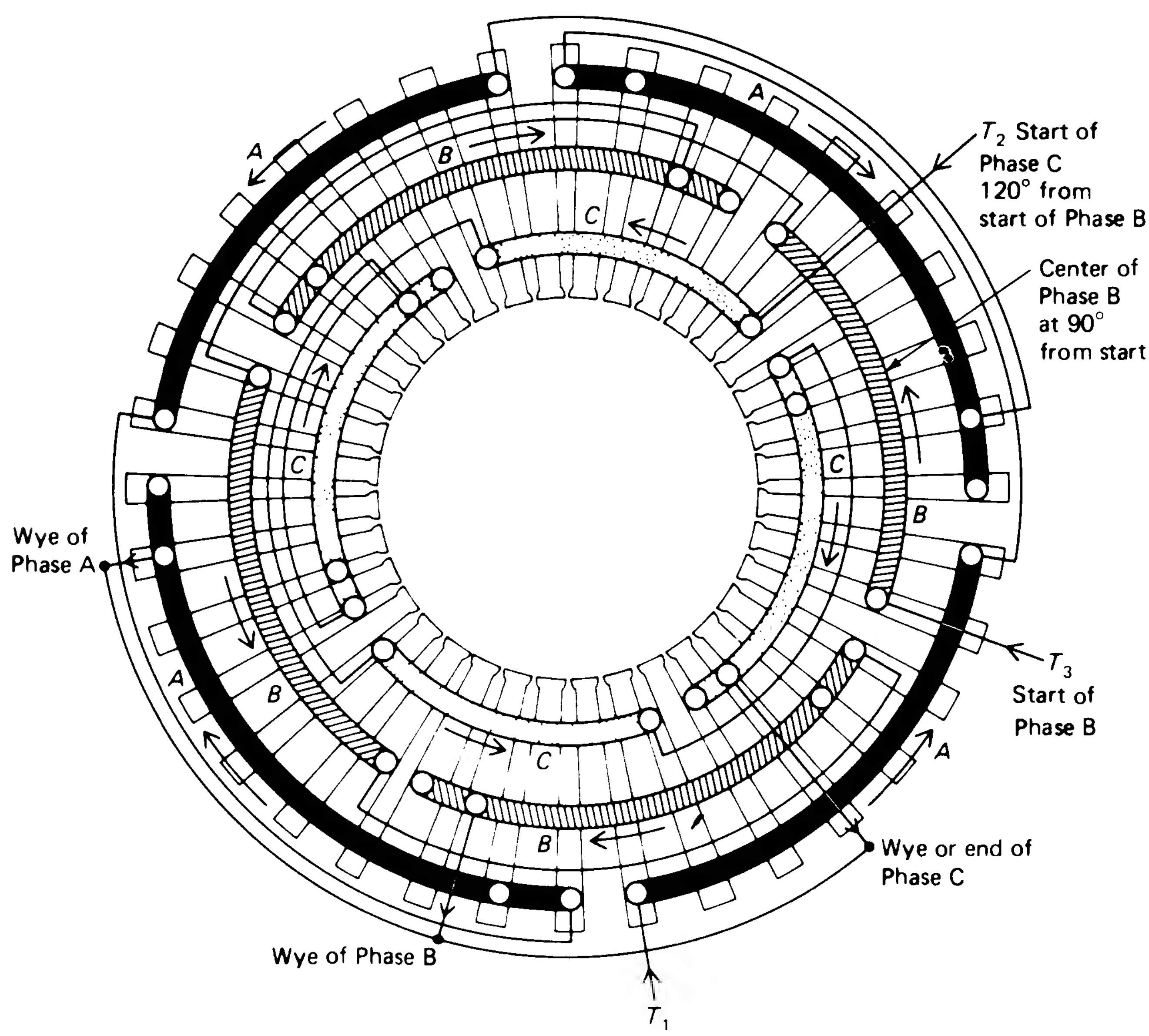


Fig. 3-110c. Start of the *C* phase at 120° to the right of the start of the *B* phase. This is the first coil located to the right of center or the 90° spot of the *B* phase and is connected at the same polarity as is the first coil of the *B* phase.

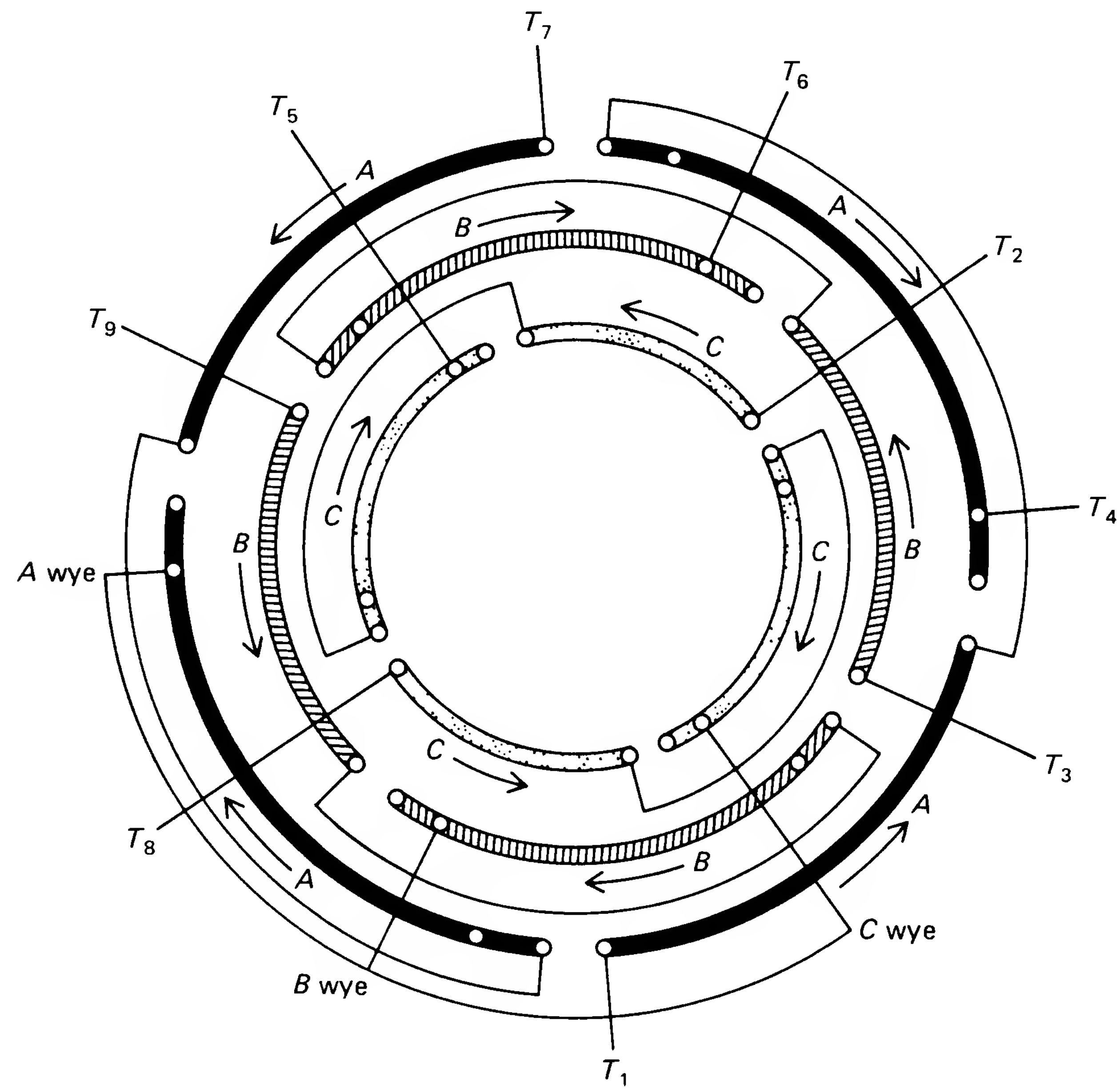


Fig. 3-111. A four-pole, short jumper, concentric, one- and two-wye connection diagram.

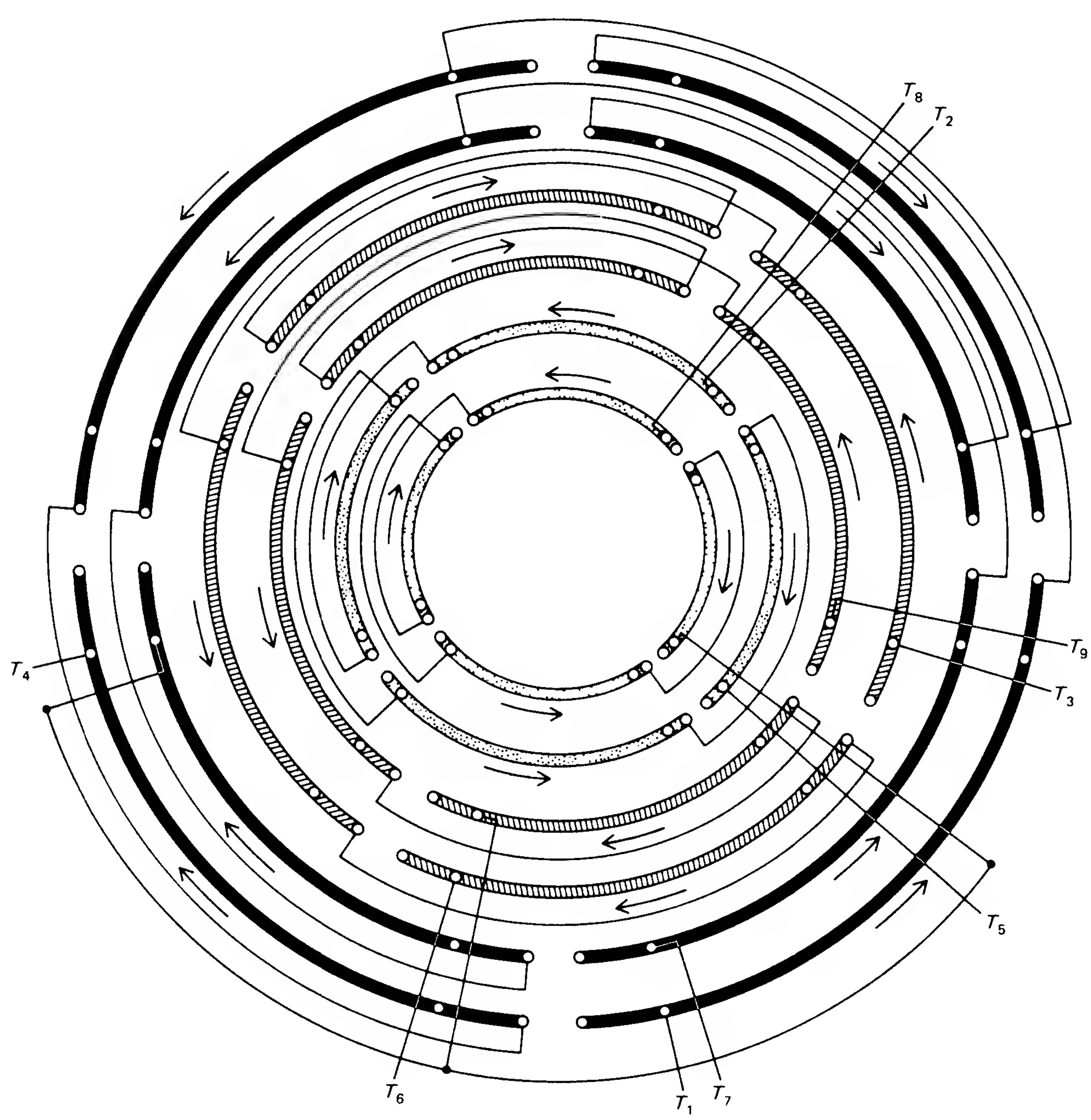


Fig. 3-112. A four-pole, concentric winding, with each coil group split into two sections and connected one and two wye.

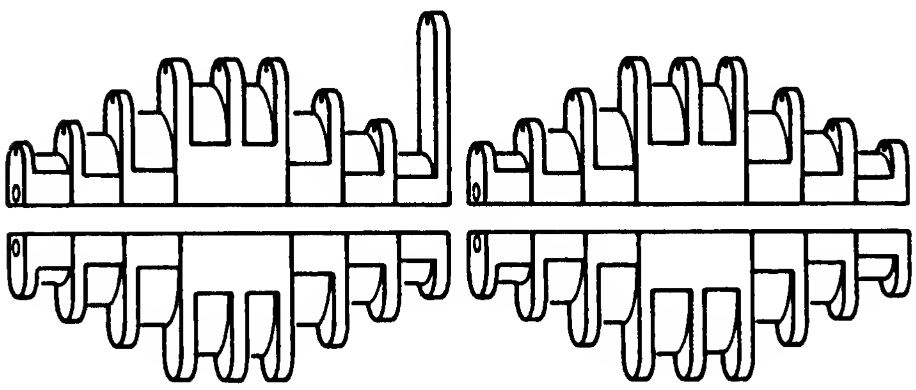


Fig. 3-113. A continuous winding head for small concentric coil groups. This head winds one complete phase with no connections between groups.

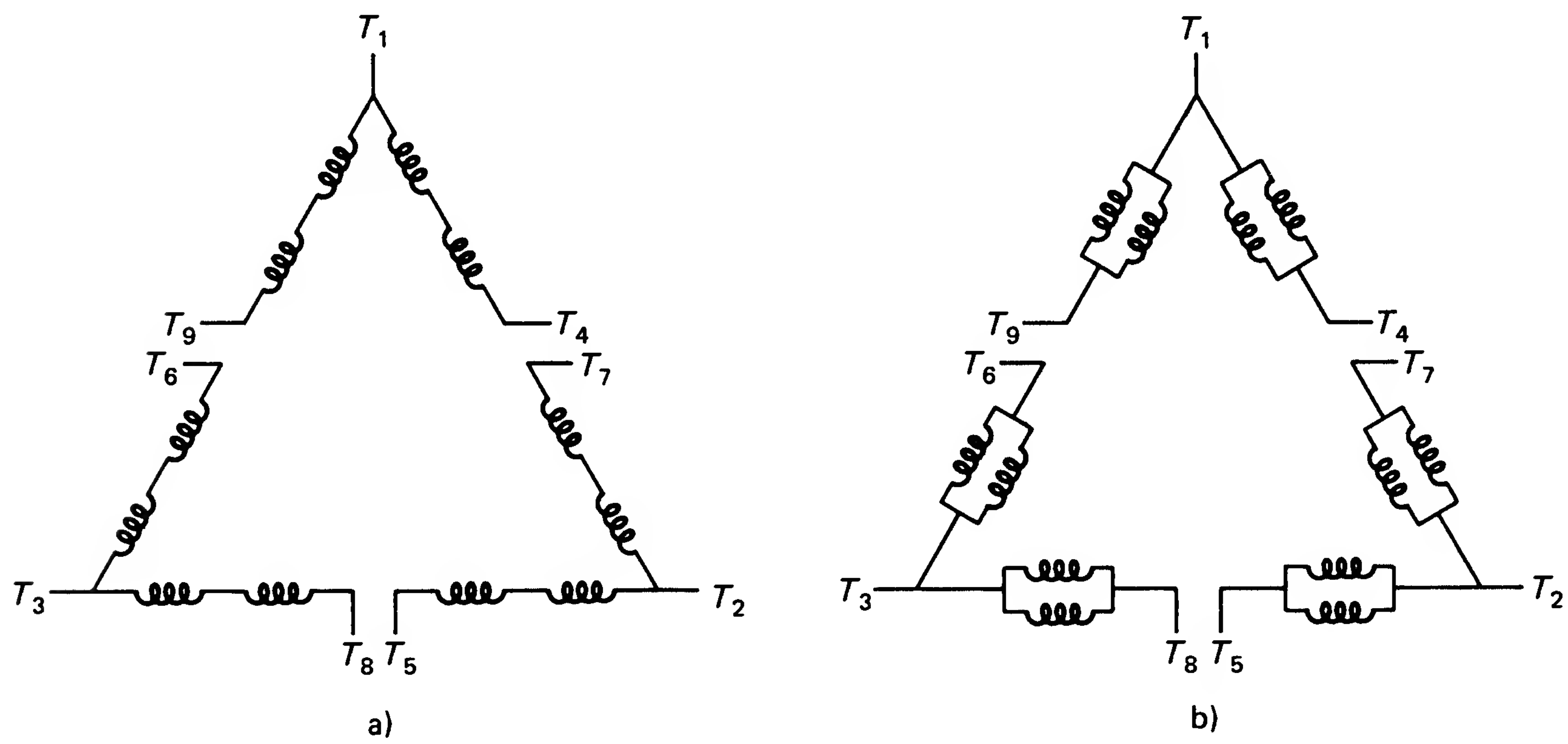


Fig. 3-114. (a) shows a four-pole, one- and two-delta connection with two groups fastened to T_1, T_2, and T_3 and one group to each of the rest. (b) is a four-pole, two- and four-delta connection with four groups fastened to T_1, T_2, and T_3, and two groups each to the rest of the leads.

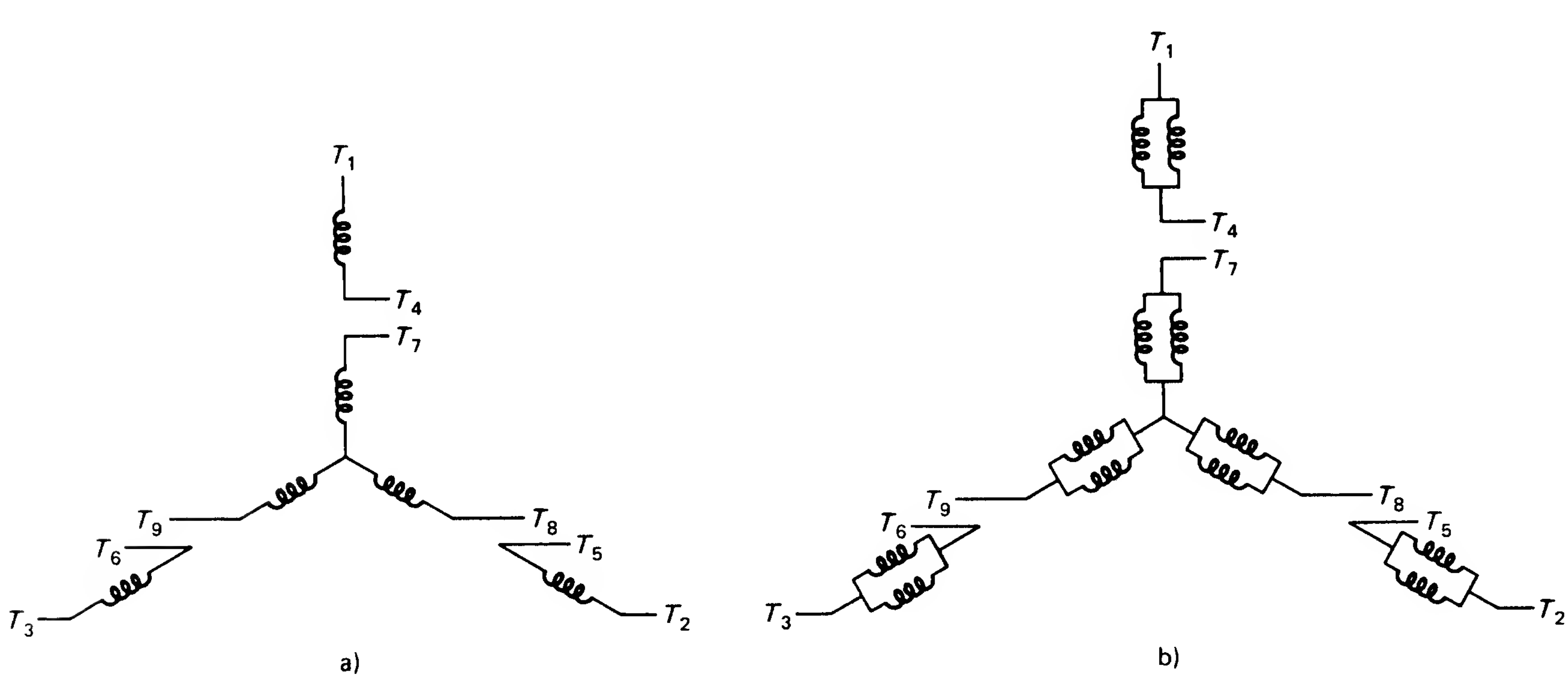


Fig. 3-115. (a) shows a four-pole, one- and two-wye connection with one group fastened to each lead and one-wye point. (b) is a four-pole two- and four-wye connection with two groups fastened to each lead and six groups tied together, forming two wyes.

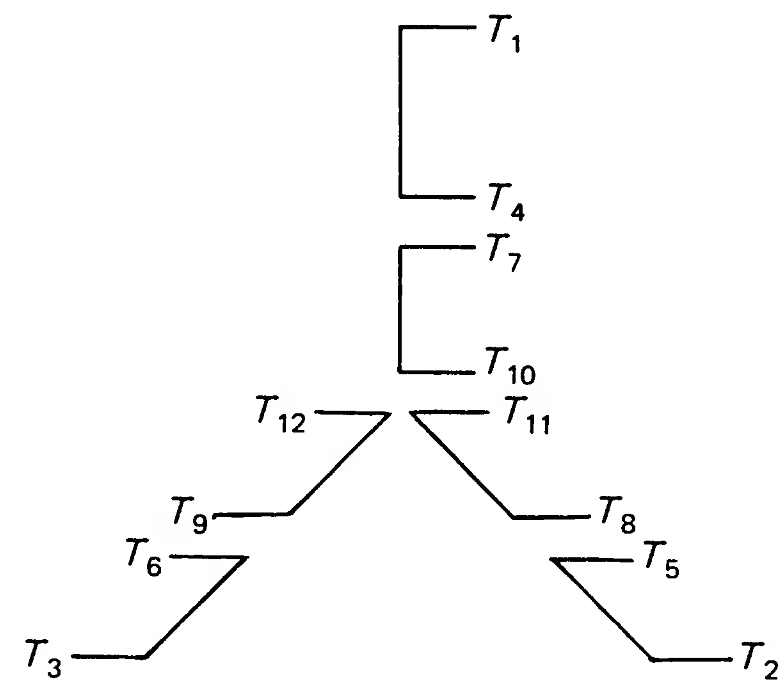


Fig. 3–116a. A 12-lead schematic, sometimes used for a part-winding start.

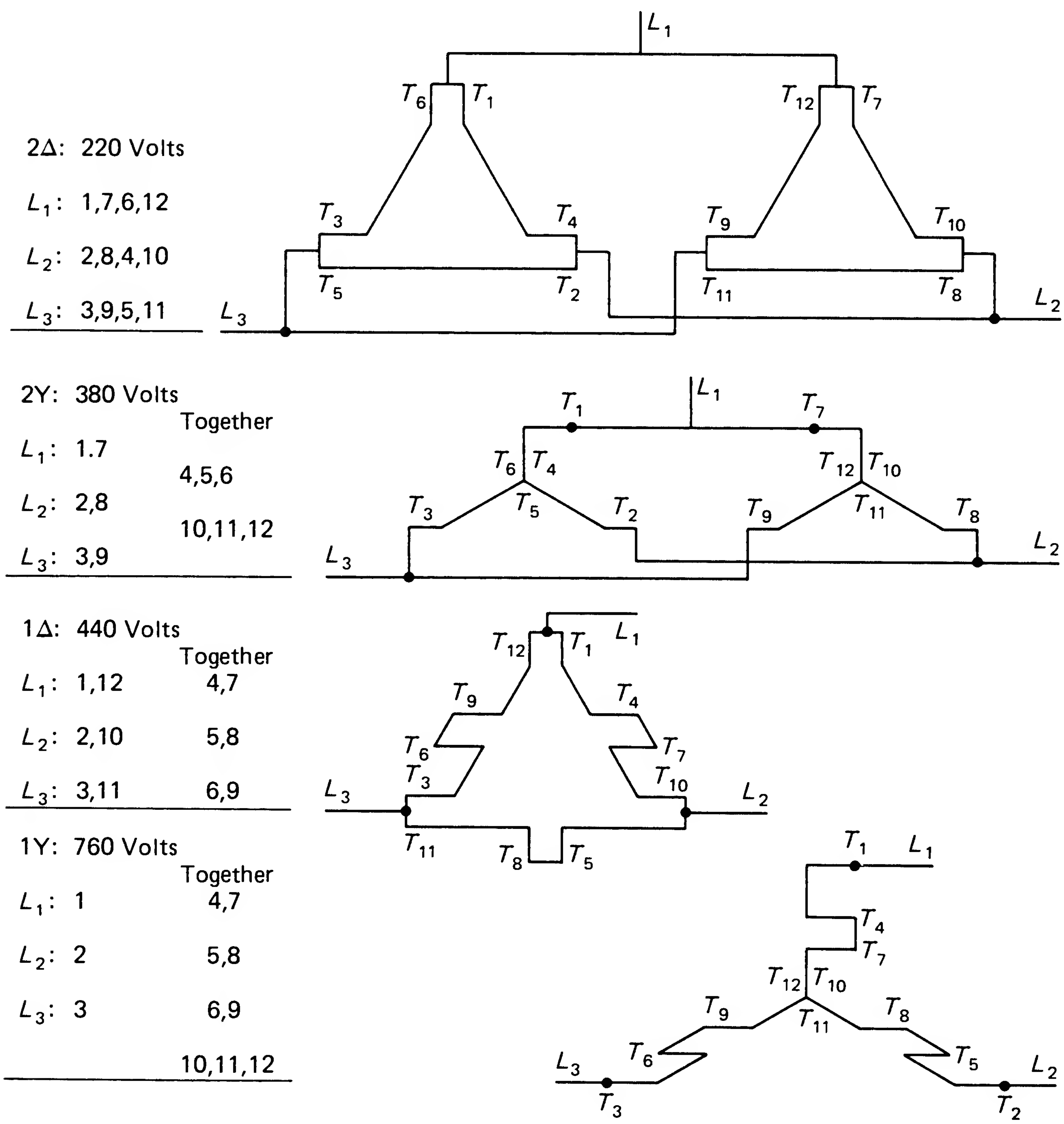


Fig. 3–116b. The voltage connections possible with a 12-lead motor.

Figures 3–116a; 3–116b

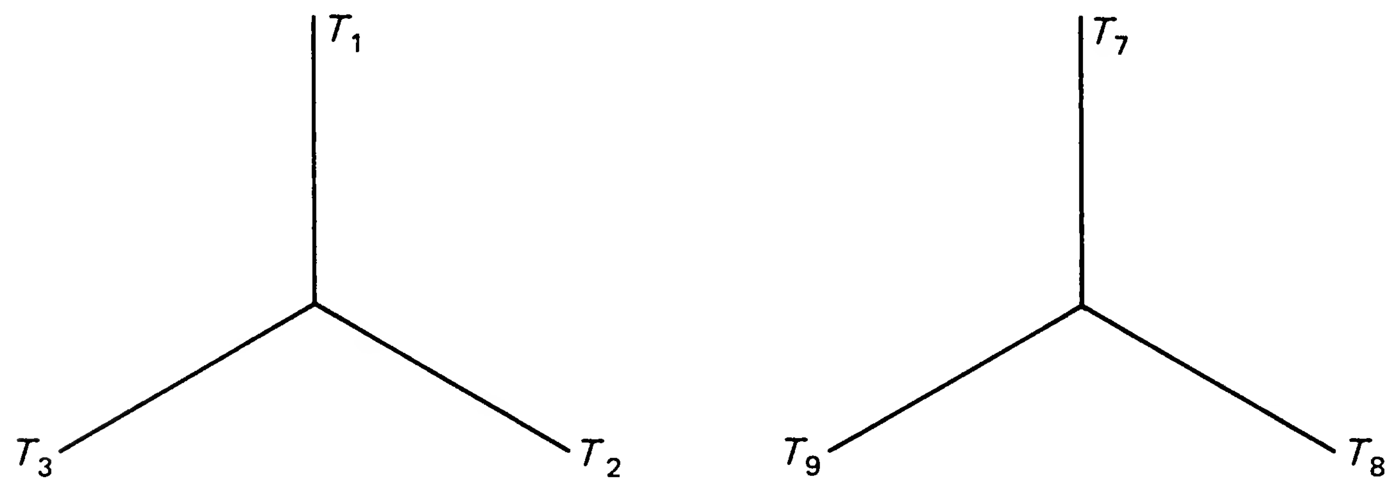


Fig. 3-117. A two-wye, six-lead motor that can be connected for a part-winding start.

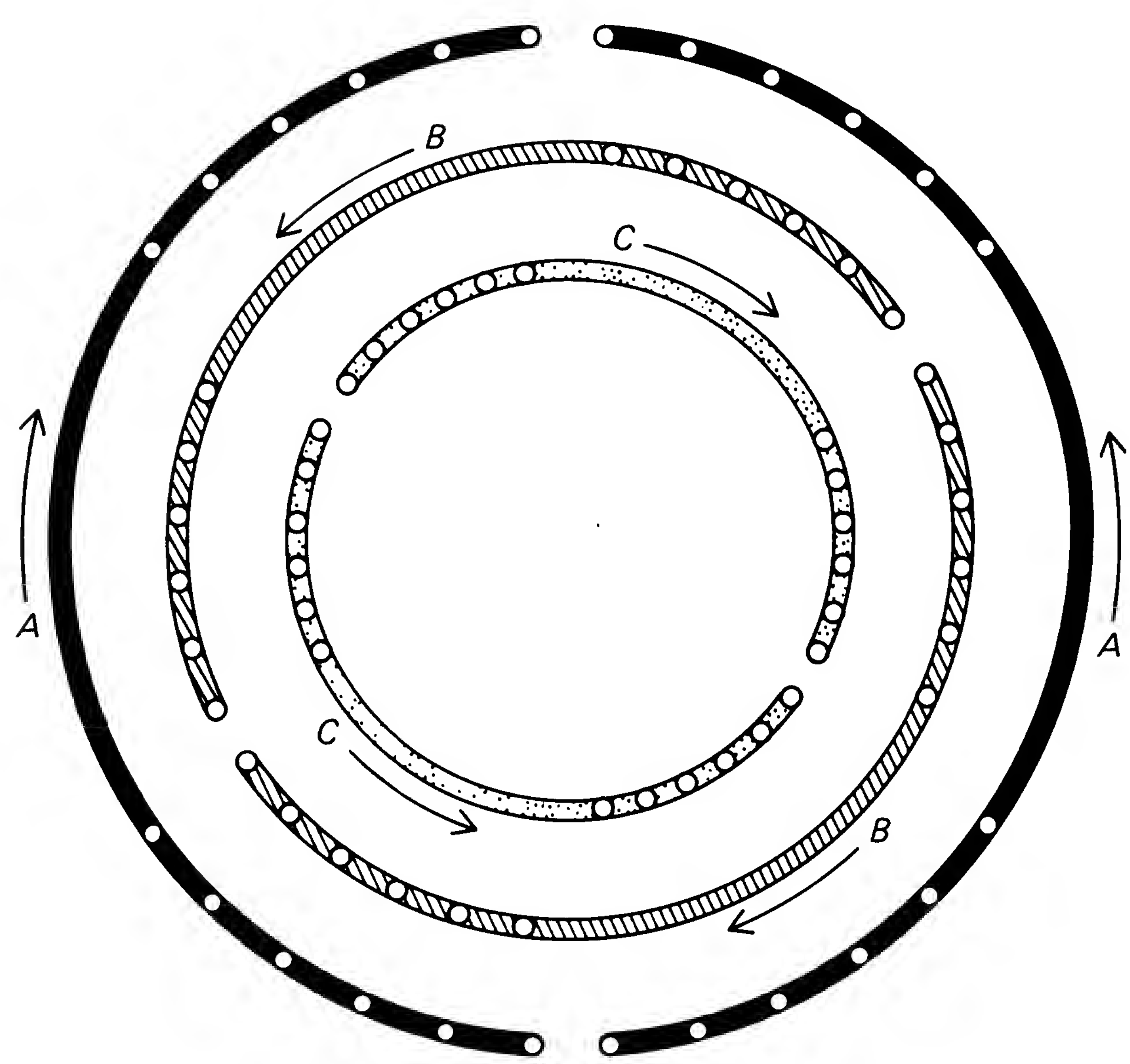


Fig. 3-118a. A two-pole concentric winding with six coil groups with six coils per group.

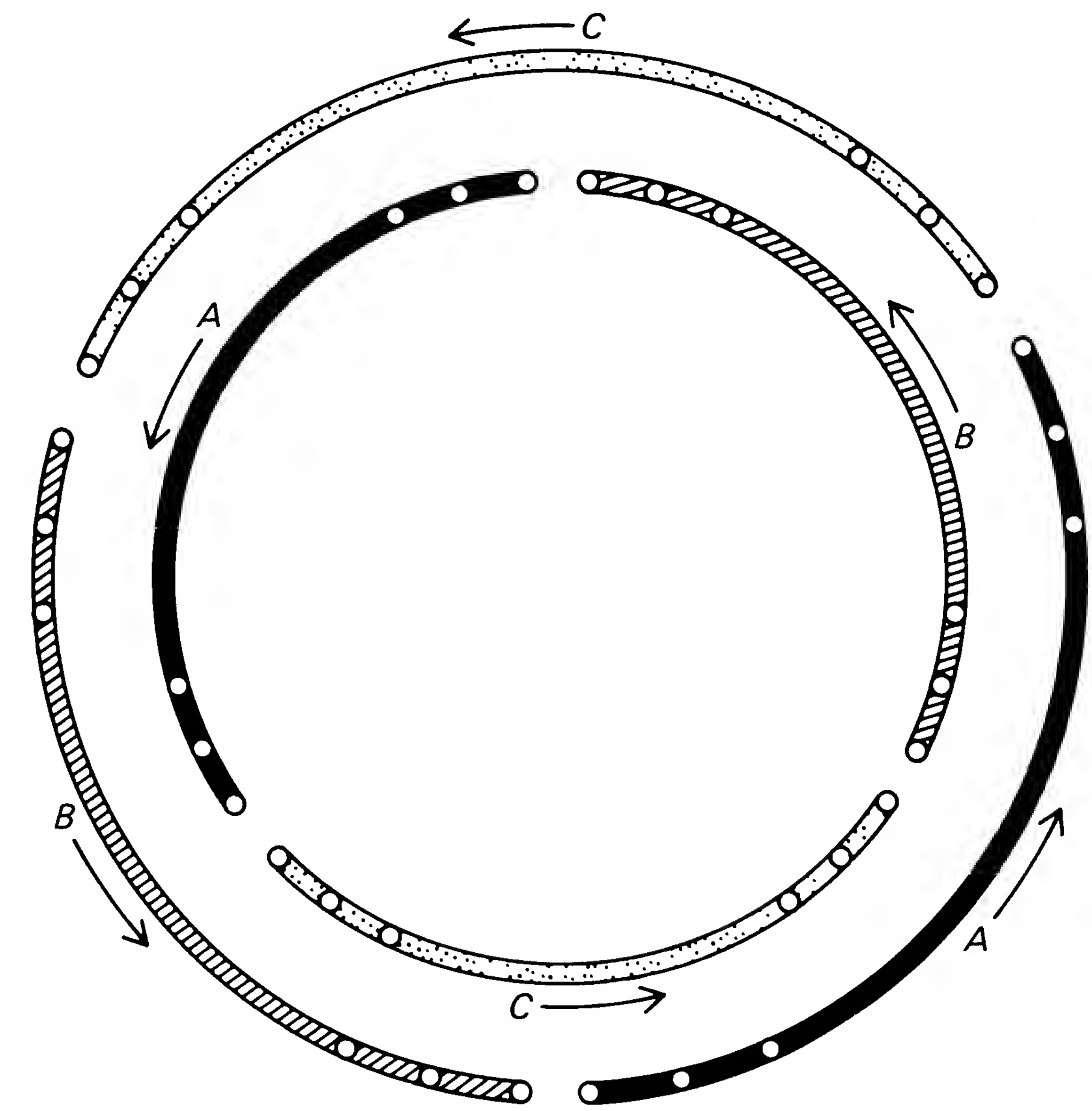
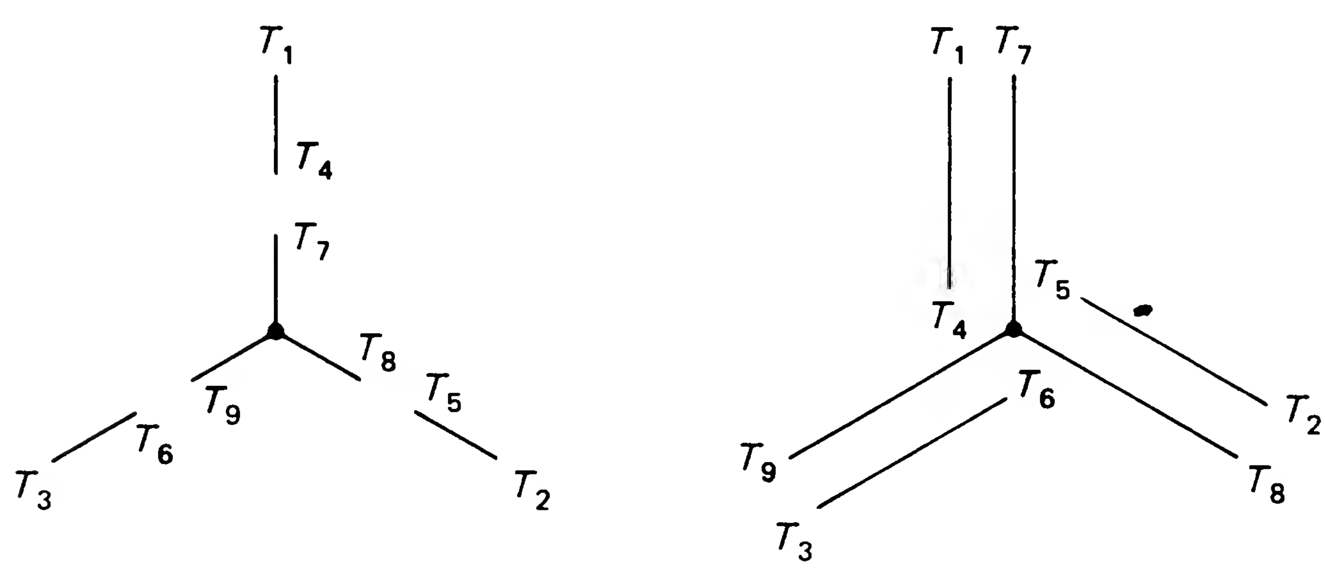


Fig. 3-118b. A four-pole concentric winding that is consequent pole. This winding also has six coil groups, like the two-pole winding.

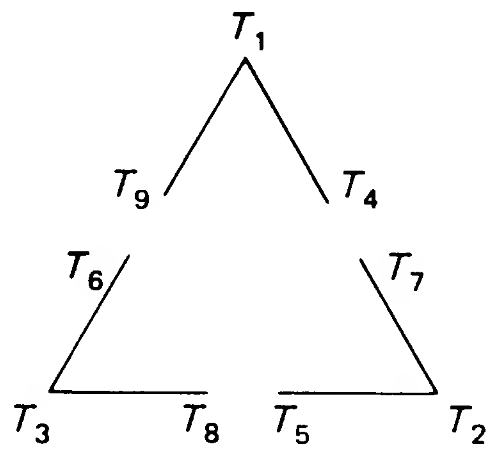


(a) Terminal markings 9 lead star (b)

Step	L_1	L_2	L_3	Tie Together
1	T_1	T_2	T_3	$T_4T_5T_6$
2	T_1T_7	T_2T_8	T_3T_9	$T_4T_5T_6$

Connector Table

Fig. 3-119a and b. Nine-lead wye connected part-winding motor. This connection can be used on any nine-lead dual-voltage motor.

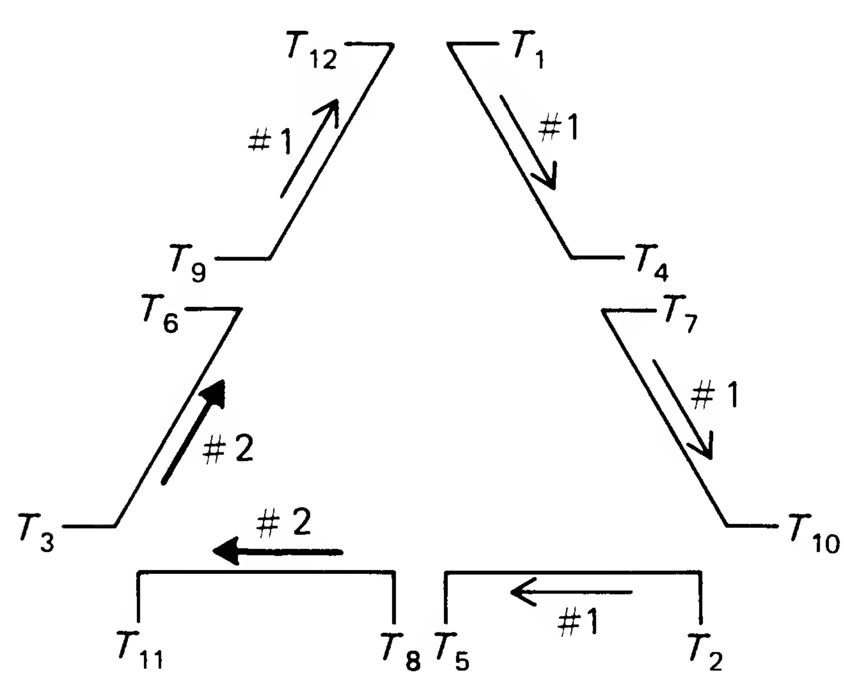


Terminal markings - 9 lead delta

Step	L_1	L_2	L_3	Tie Together
1	T_1T_6	T_2T_4	T_3T_5	
2	$T_1T_6T_7$	$T_2T_4T_8$	$T_3T_5T_9$	

Step	L_1	L_2	L_3	Tie Together		
1	T_1	T_4T_2	T_9	T_4T_8	T_5T_9	T_6T_7
2	T_1T_6	T_4T_2	T_9T_3	T_4T_8	T_5T_9	T_6T_7

Fig. 3-120a. Two methods of connecting a nine-lead delta part-winding motor.



Step	L_1	L_2	L_3
1	T_1 T_7 T_{12}	T_2 T_4 T_{10}	T_5 T_9 T_{11}
2	T_1 T_7 T_{12} T_6	T_2 T_4 T_{10} T_8	T_5 T_9 T_{11} T_3

Fig. 3-120b. A 12-lead, delta motor connection for a ⅔ part-winding start. The outside arrows indicate the windings energized in the first step, and the inside arrows are the windings energized on the second step.

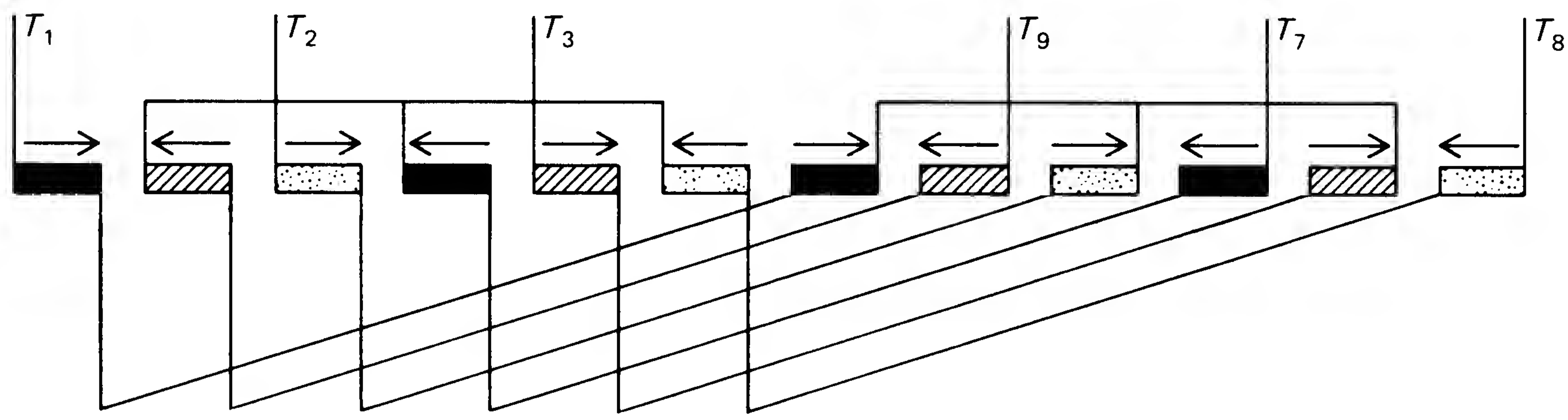


Fig. 3-121. A six-lead, four-pole, long jumper, two-wye connection that can be used for a part-winding start.

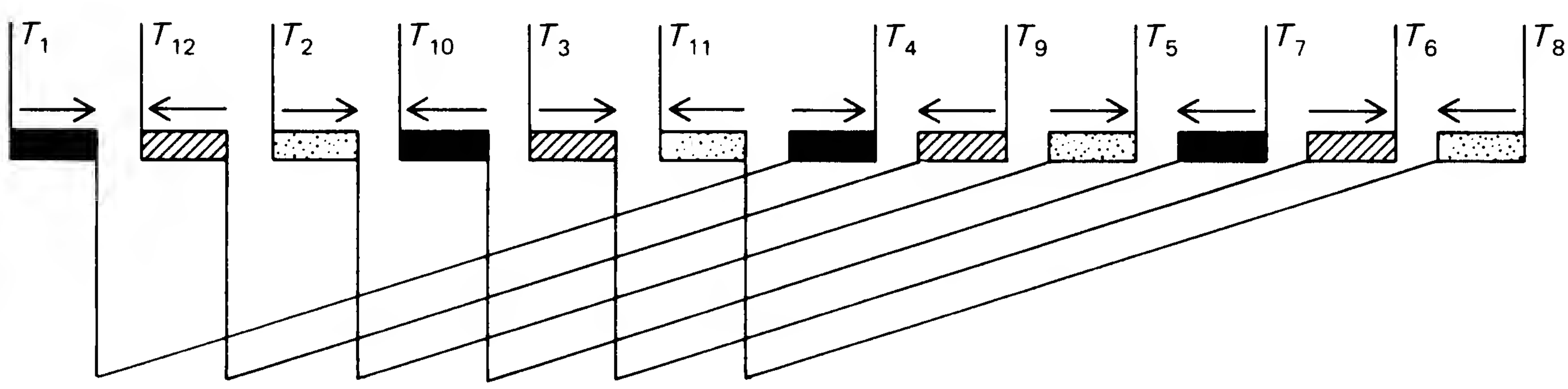


Fig. 3-122. A 12-lead, four-pole, long jumper, one- and two-delta connection that can be used as part winding start for ½ or ⅔ winding. This connection can also be used as wye start, delta run (wye-delta), and one and two wye.

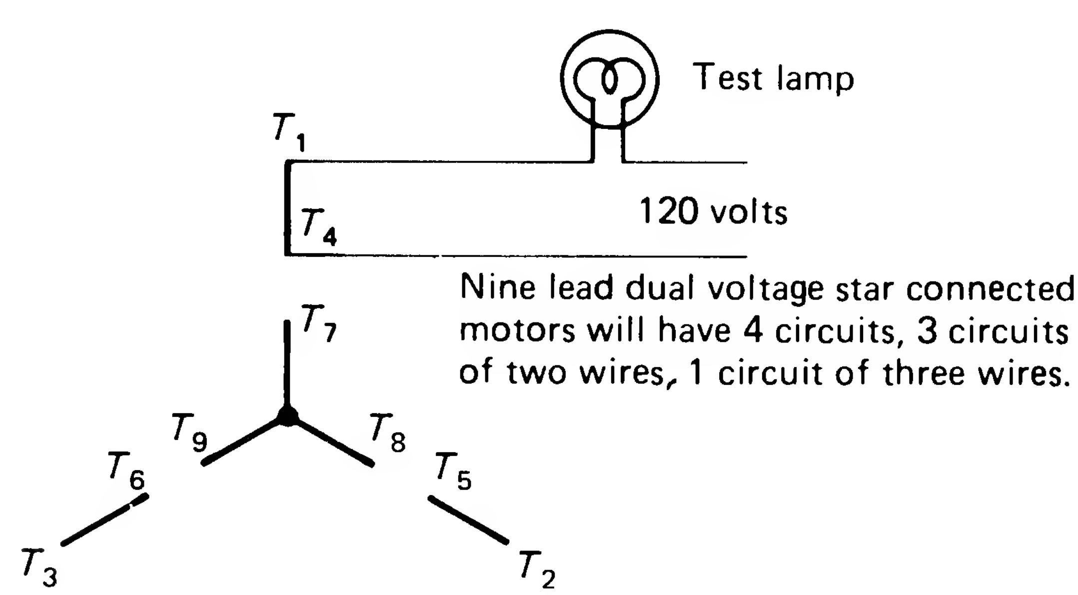


Fig. 3-123a. Testing each circuit for continuity.

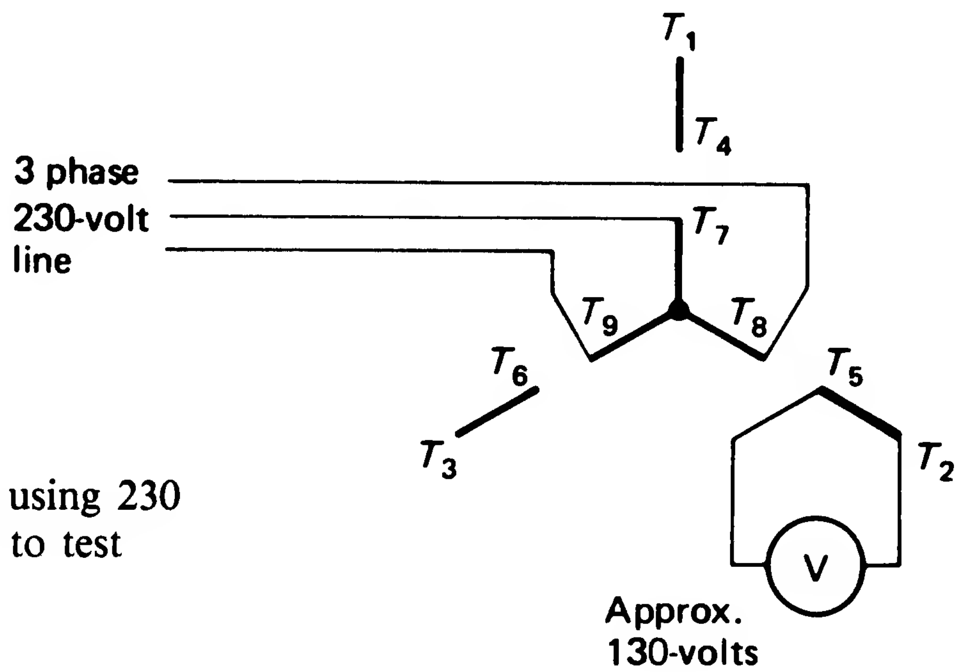


Fig. 3-123b. Run motor using 230 volts 3 phase across T_7, T_8, T_9 to test voltage across each section.

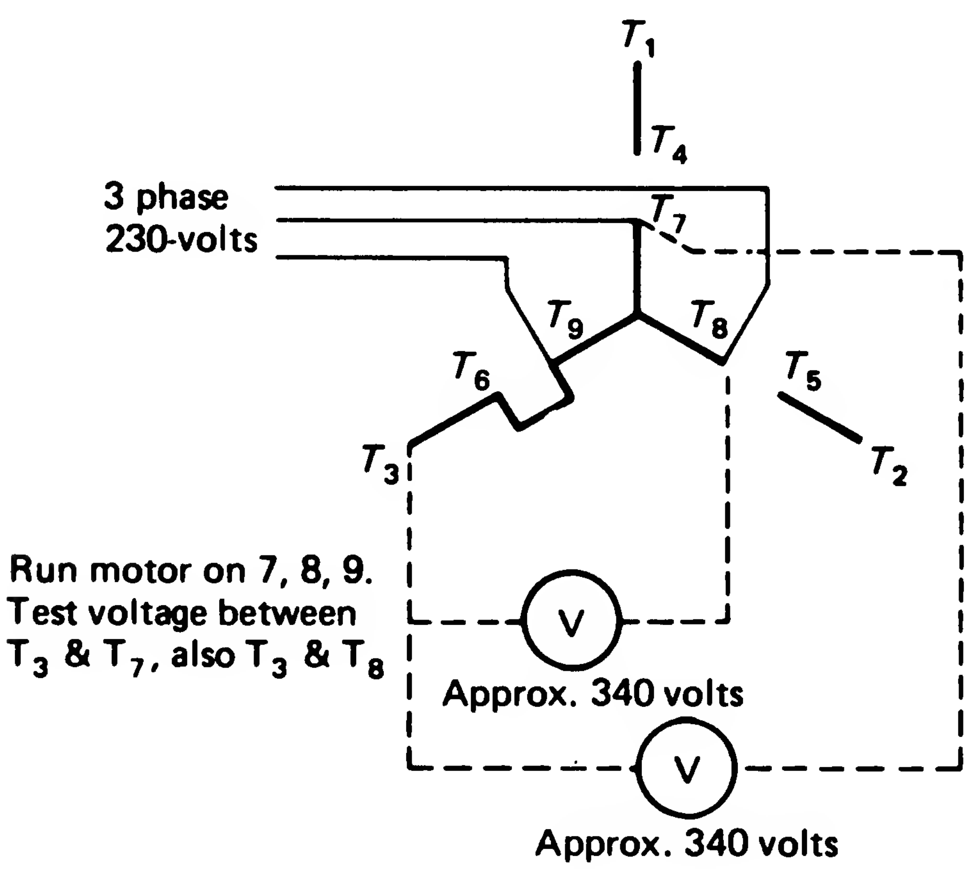


Fig. 3-123c. Testing for correct connections in each phase.

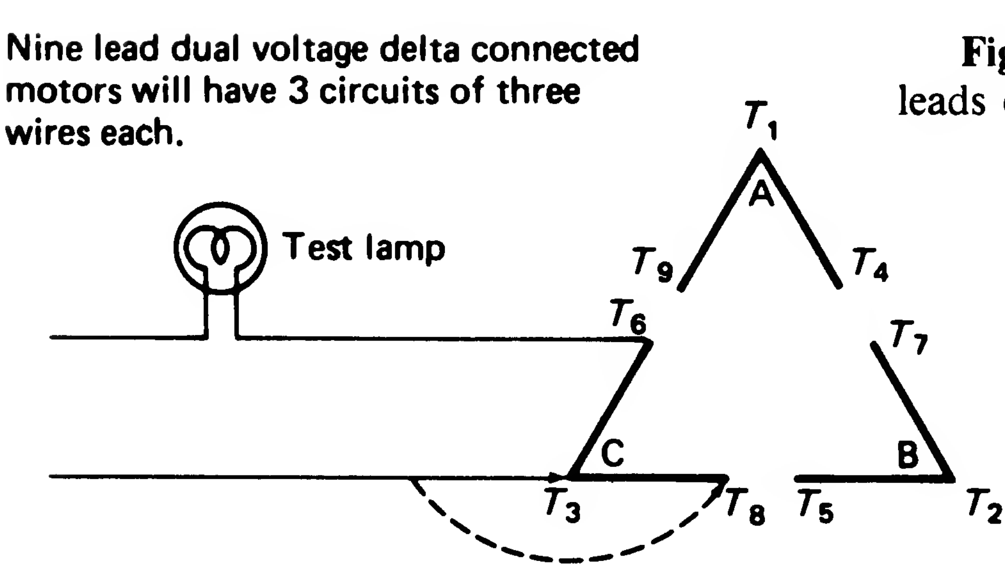


Fig. 3-124a. Test for 3 circuits of 3 leads each.

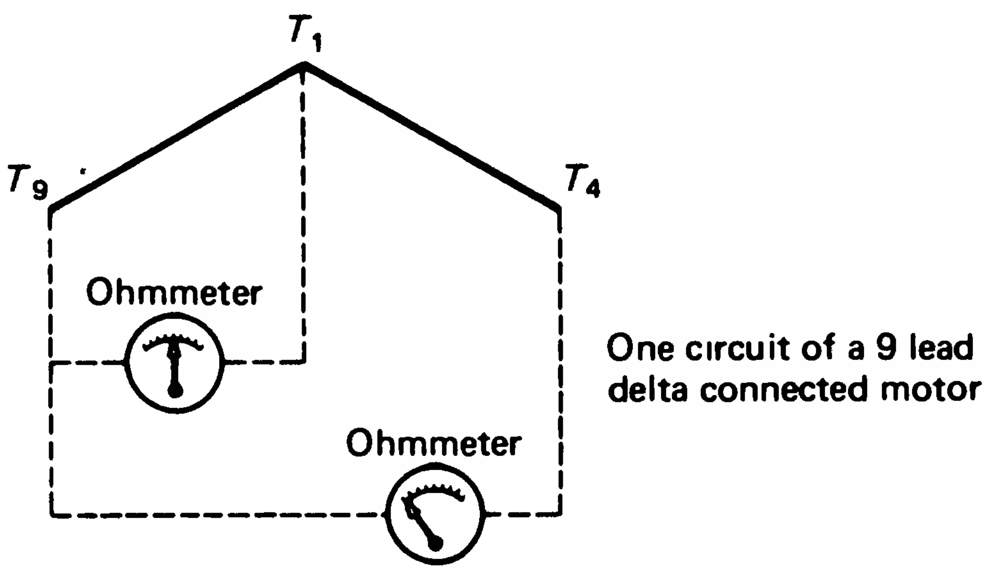


Fig. 3–124b. Measuring resistances with ohmmeter resistance between T_9 and T_4 = 2 times that of T_9 and T_1.

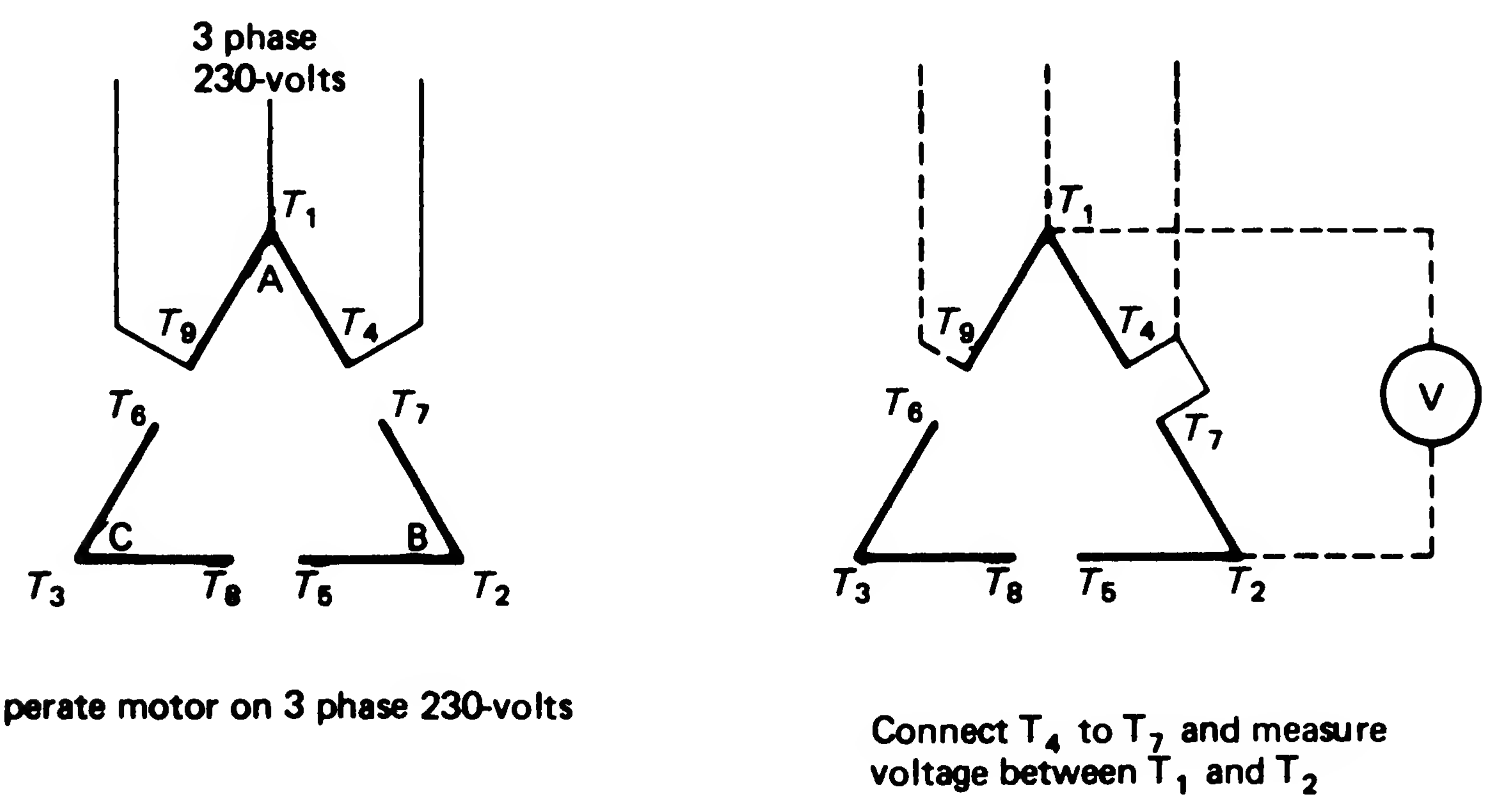


Fig. 3–124c. Connecting circuits to their proper phases.

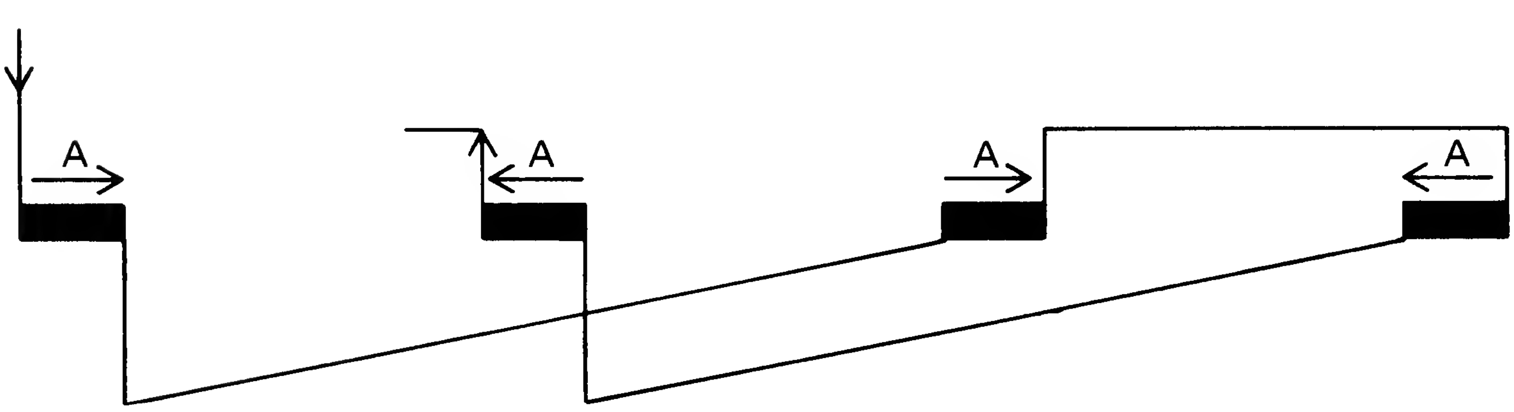


Fig. 3–125. The polarity of the *A* phase of a normal long jumper, four-pole motor.

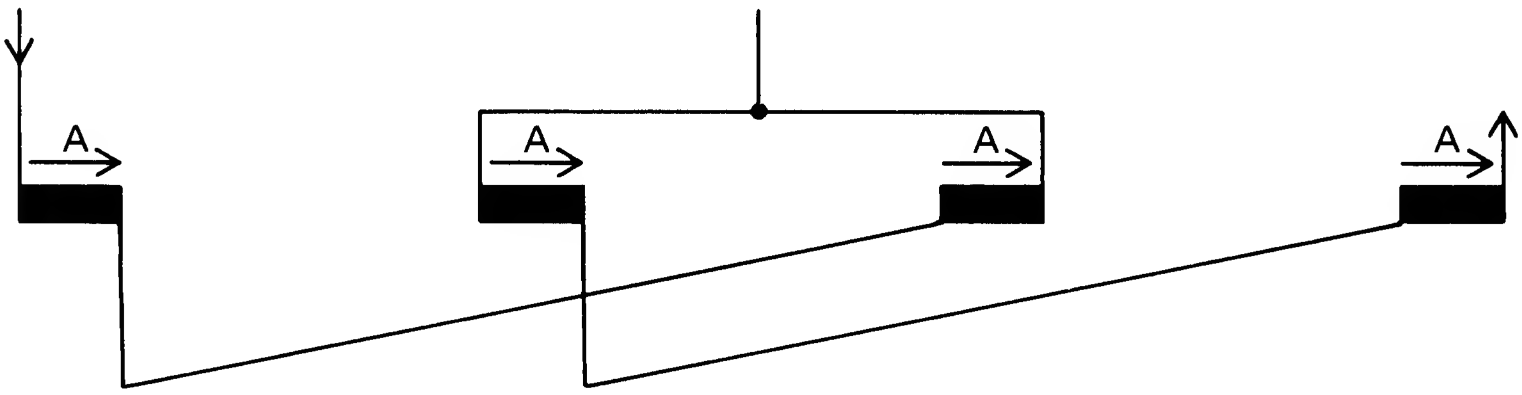


Fig. 3–126. The polarity of the *A* phase of a consequent-pole, two-speed, constant-torque motor connected for low speed. All four poles have the same polarity, and so eight poles will form in the stator.

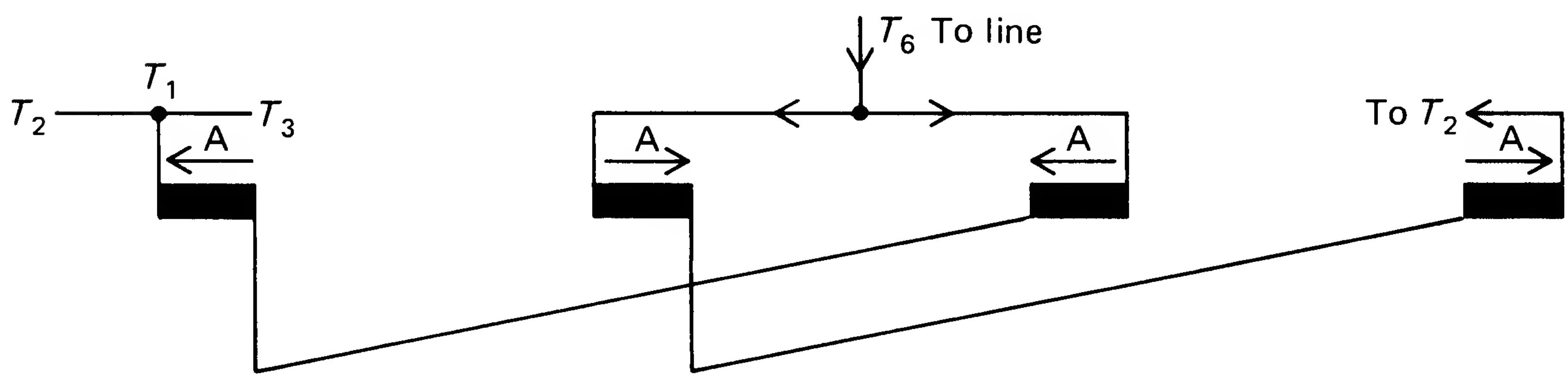


Fig. 3–127. The polarity of the *A* phase of a constant-torque motor when connected two wye for high speed. All one-winding, two-speed motors are connected long jumper.

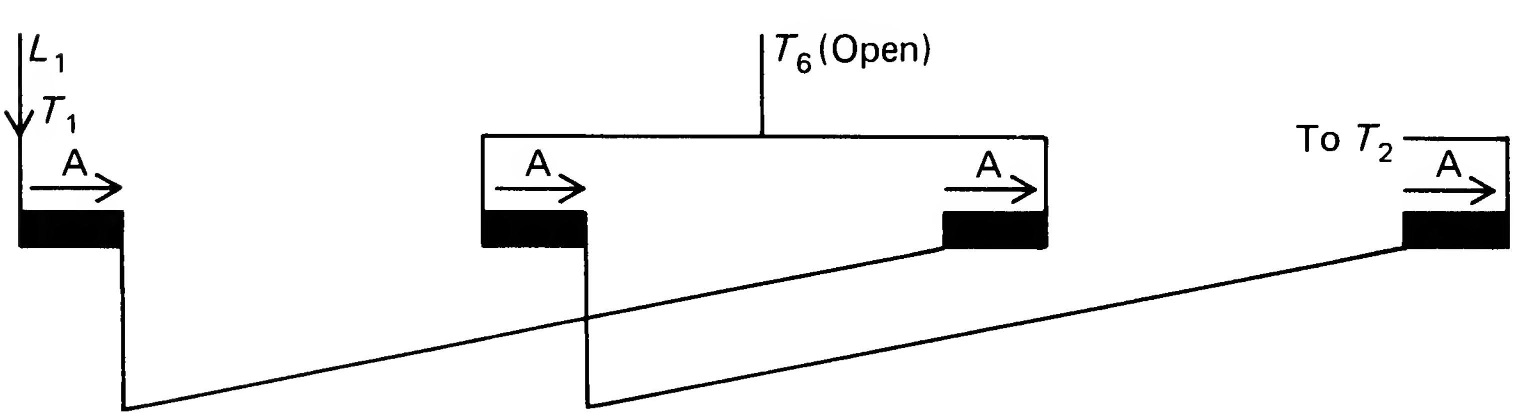
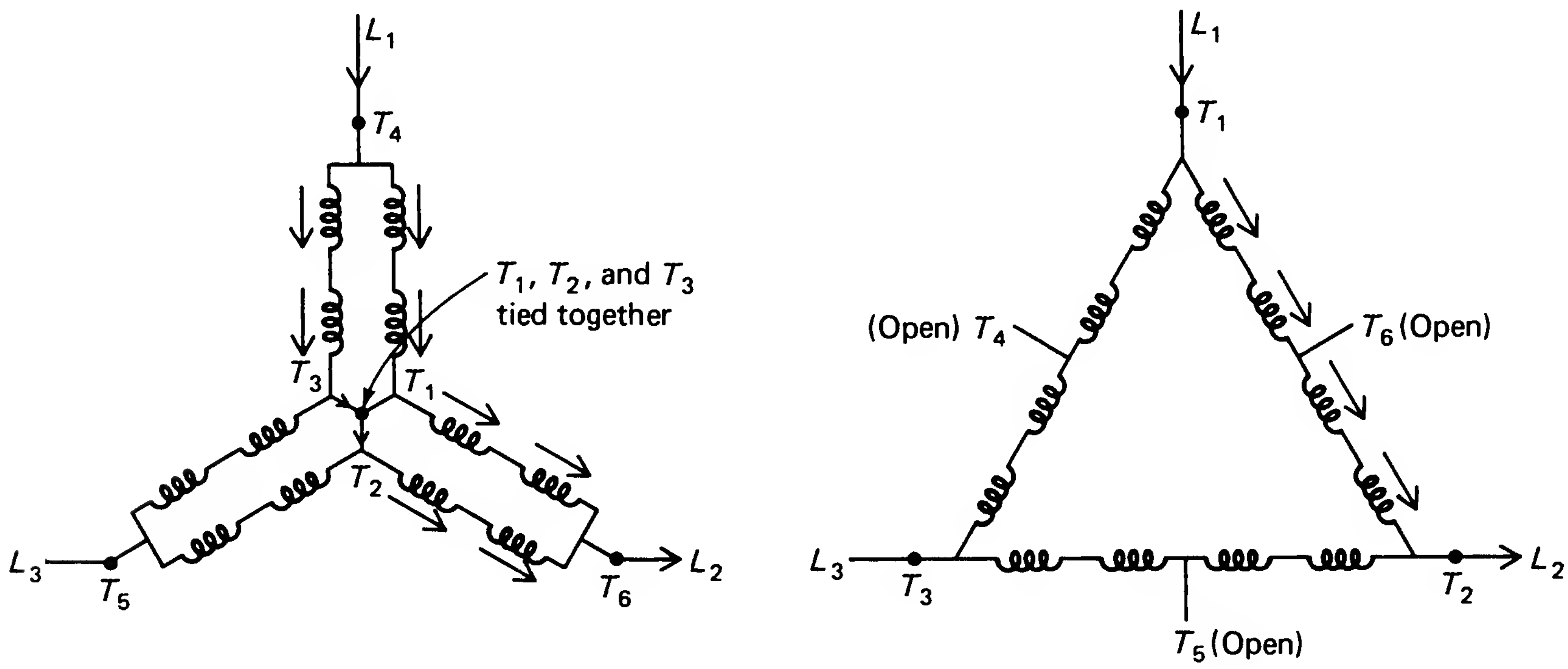


Fig. 3–128. Phase *A* connected series-delta for eight-pole operation. The current flows through the groups in the direction of the arrows. This type of motor will have the same torque at both speeds.



a) Four-pole b) Eight-pole

Fig. 3-129. A two speed, constant-torque schematic connected for (a) high speed, four poles, and two wye and (b) for low speed, eight poles, and one delta. The arrows show the path from L_1 to L_2.

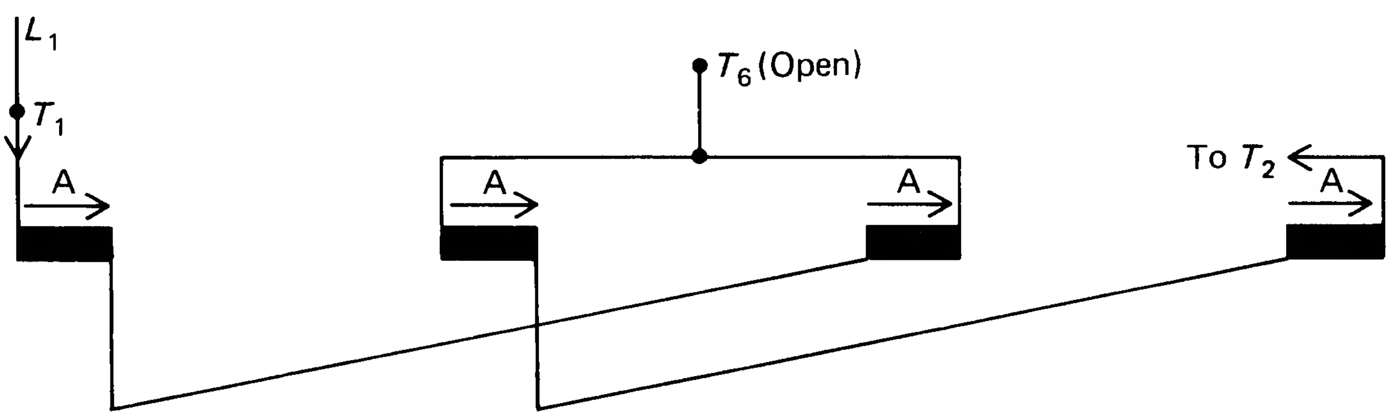


Fig. 3-130a. Phase A of a constant-torque motor connected one delta for low speed.

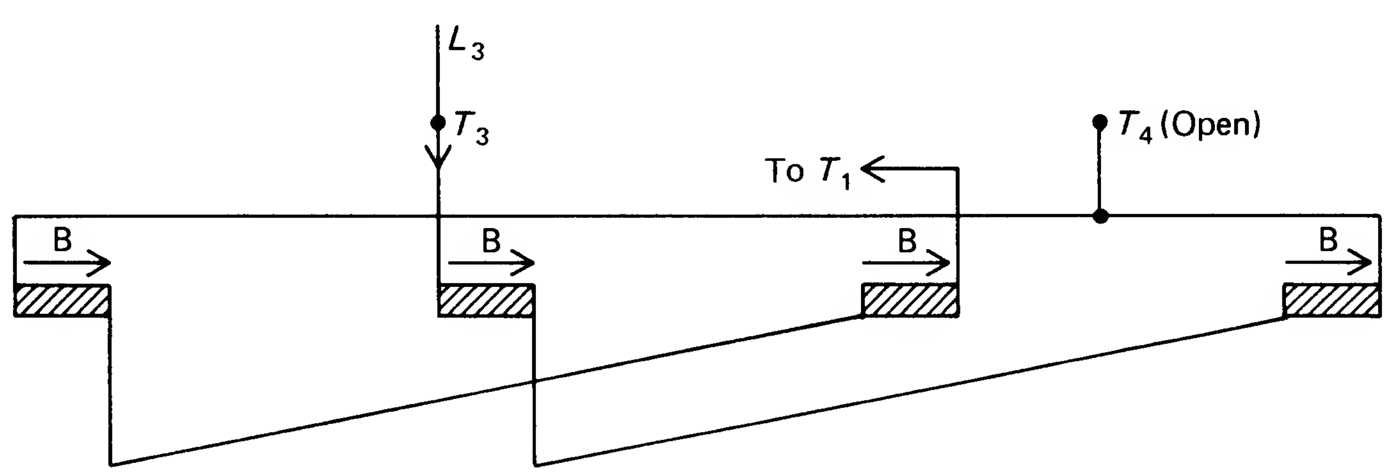


Fig. 3-130b. Phase B of a constant-torque motor connected one delta for low speed.

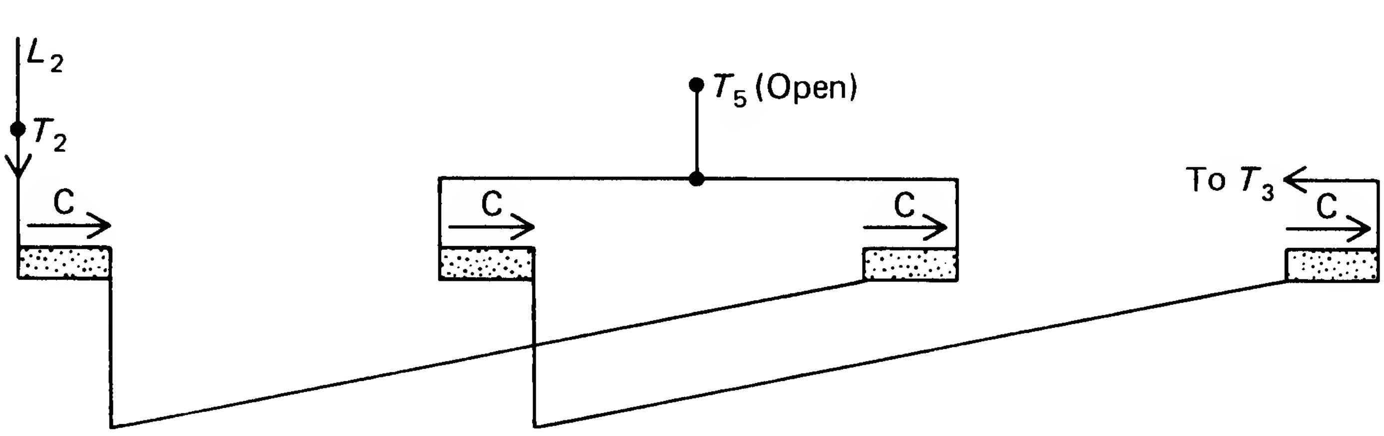


Fig. 3-130c. Phase C of a constant-torque motor, connected one delta for low speed.

Figures 3-129; 3-130a; 3-130b; 3-130c

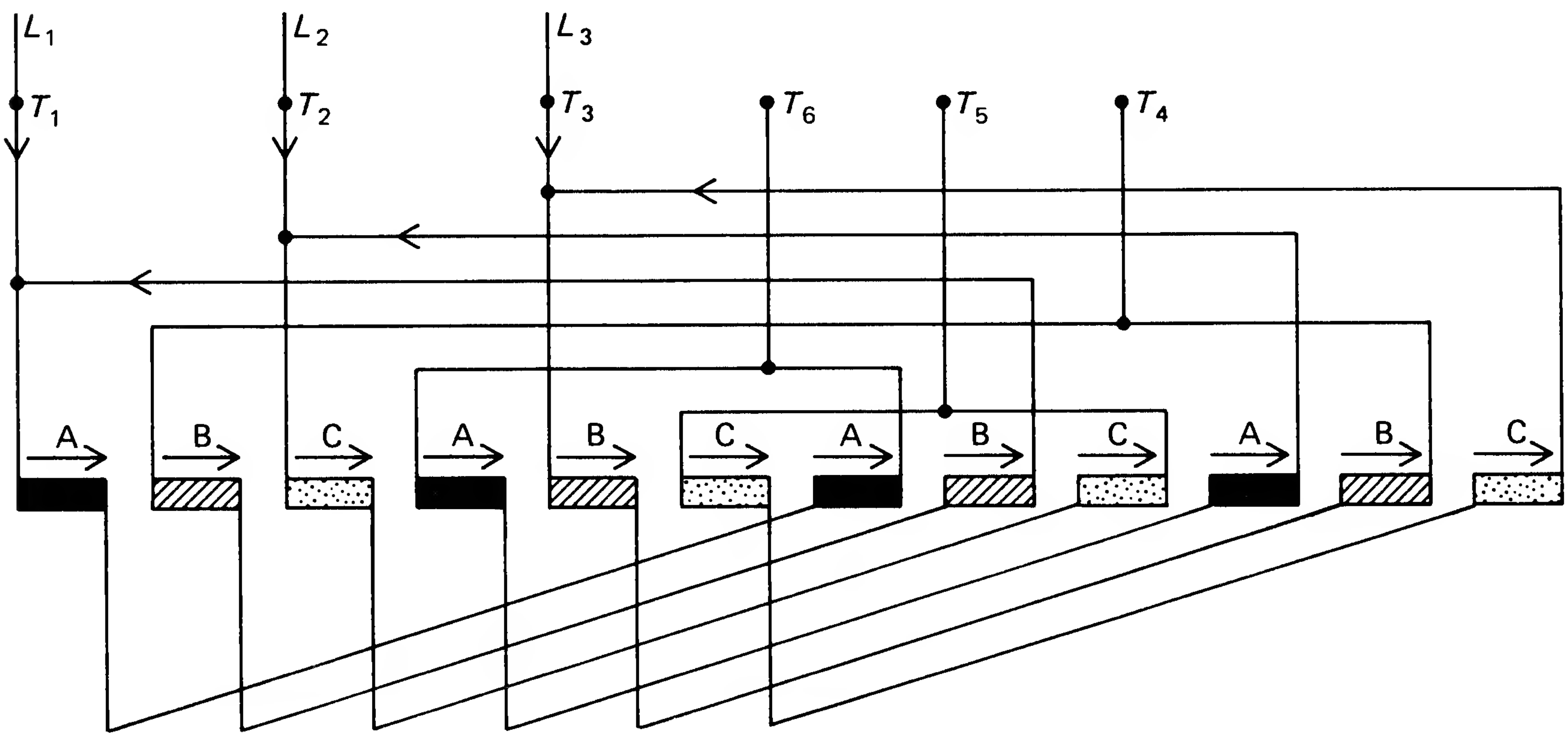
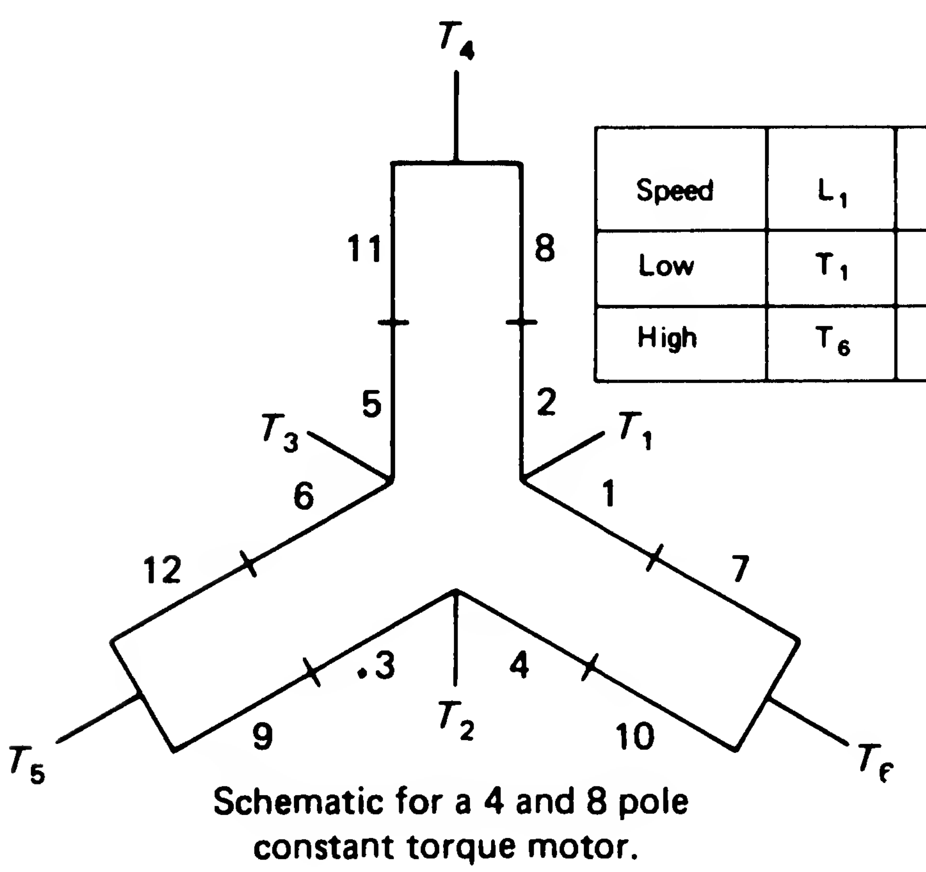


Fig. 3-130d. A four- and eight-pole constant-torque motor connected for low speed. T_4, T_5, and T_6 are separately insulated for this connection.



Speed	L_1	L_2	L_3	Insulate Separately	Tie Together
Low	T_1	T_2	T_3	$T_4T_5T_6$	
High	T_6	T_4	T_5		$T_1T_2T_3$

Fig. 3-130e. A four-pole, constant-torque two-speed motor. The parallel-star (2Y) connection is used for high-speed operation; the series-delta for low-speed operation. T_4, T_5, T_6 to line; T_1, T_2, T_3 connected together, for high speed. T_1, T_2, T_3 to line; T_4, T_5, T_6 not connected, for low speed.

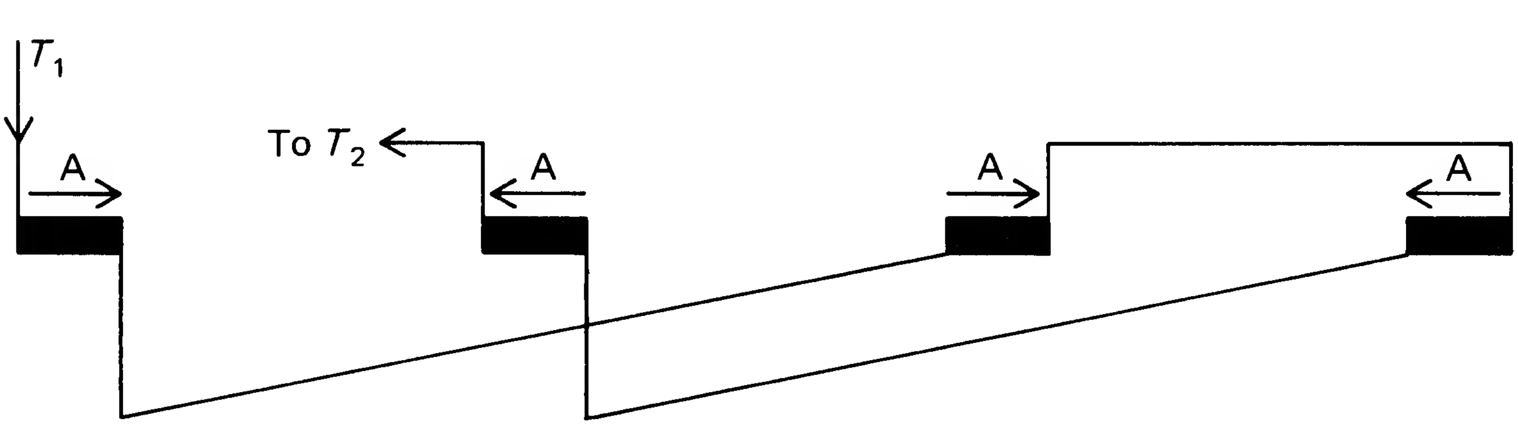


Fig. 3-131a. Phase *A* of a one-delta, four-pole motor.

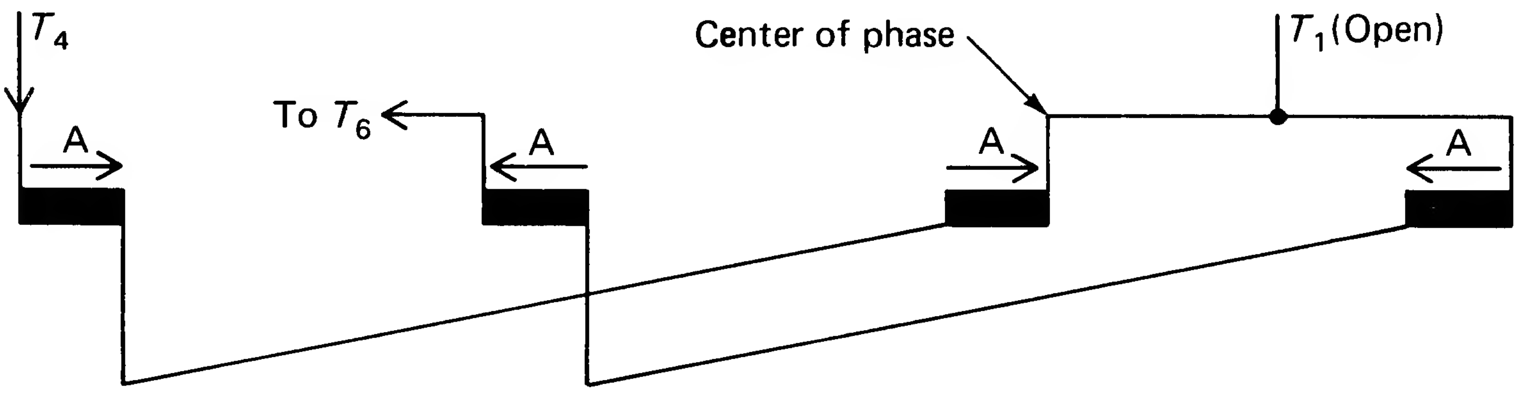


Fig. 3-131b. Phase A of a constant-horsepower, one-delta, two-wye, four- and eight-pole motor connected four poles, one delta.

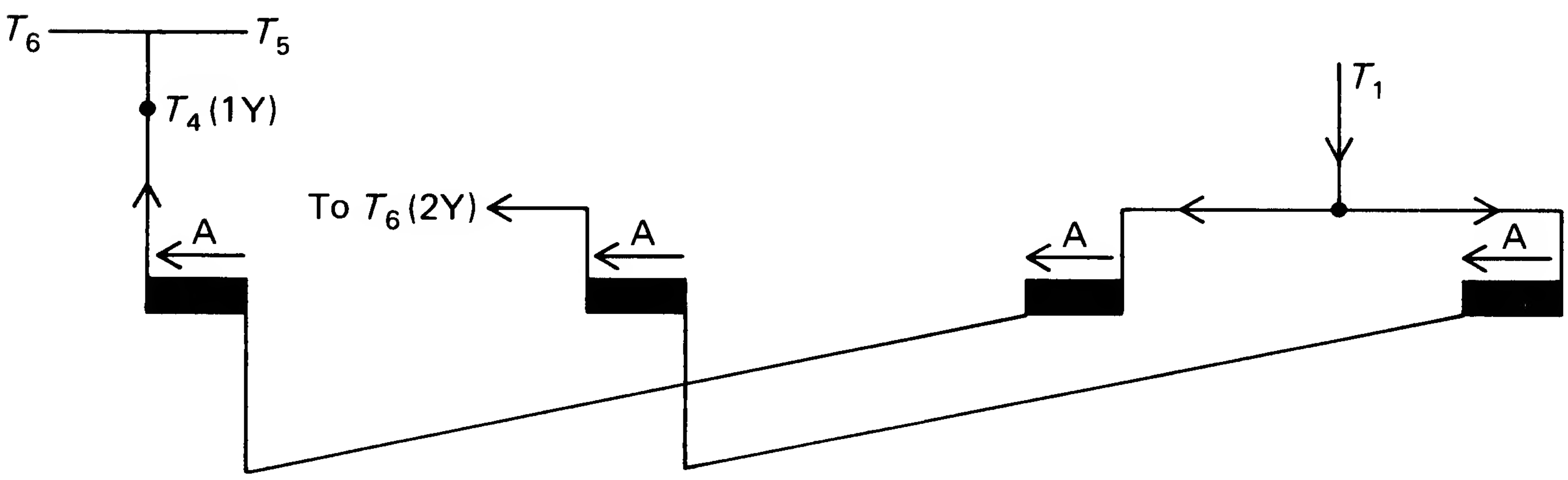


Fig. 3-131c. Phase A of a constant-horsepower, one-delta, two-wye, four- and eight-pole motor connected eight poles, two wye.

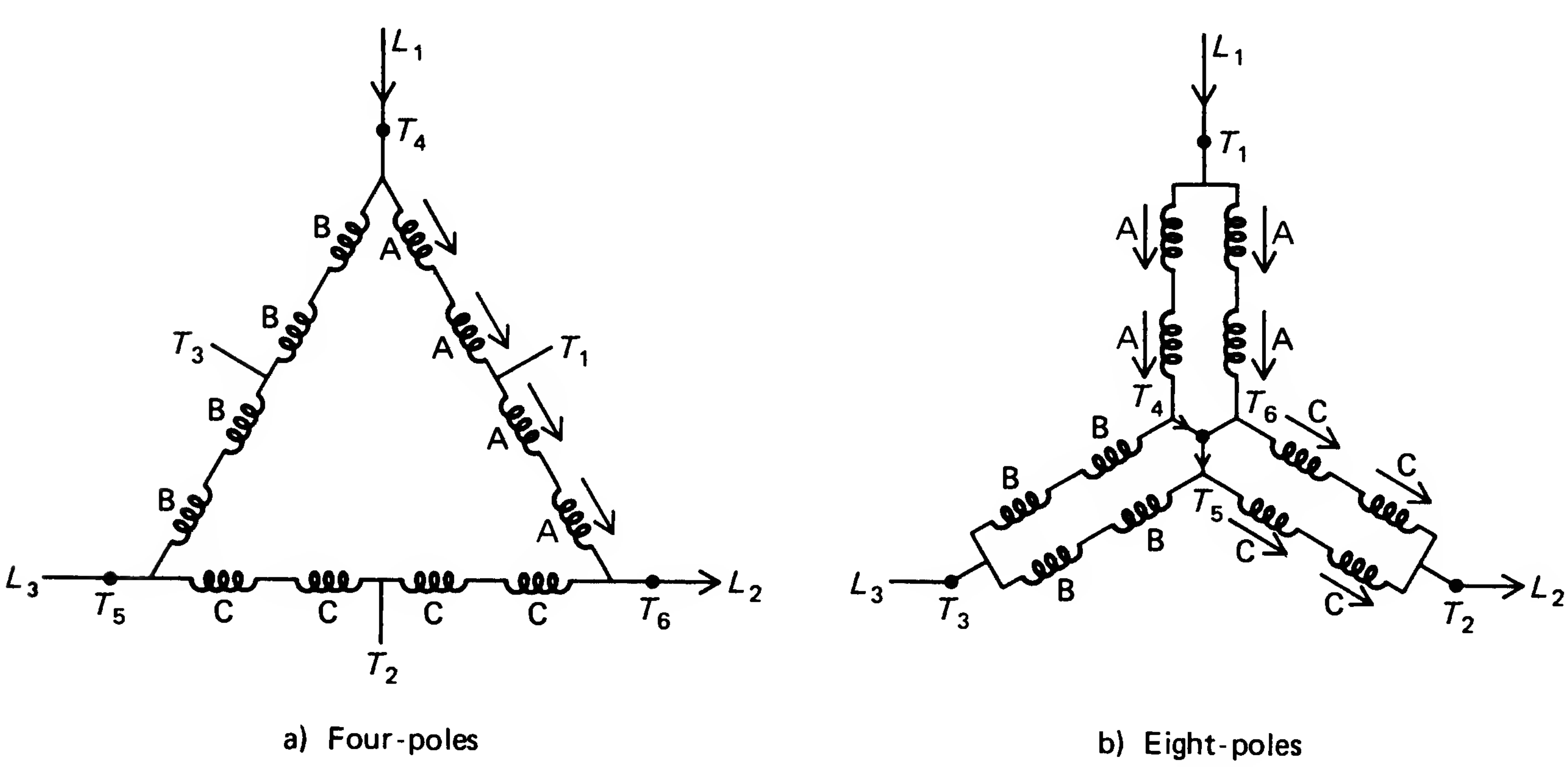


Fig. 3-132. A two-speed, constant-horsepower schematic diagram, connected (a) for high speed, four poles, and series-delta and (b) for low speed, eight poles, and two wye.

Figures 3-131b; 3-131c; 3-132

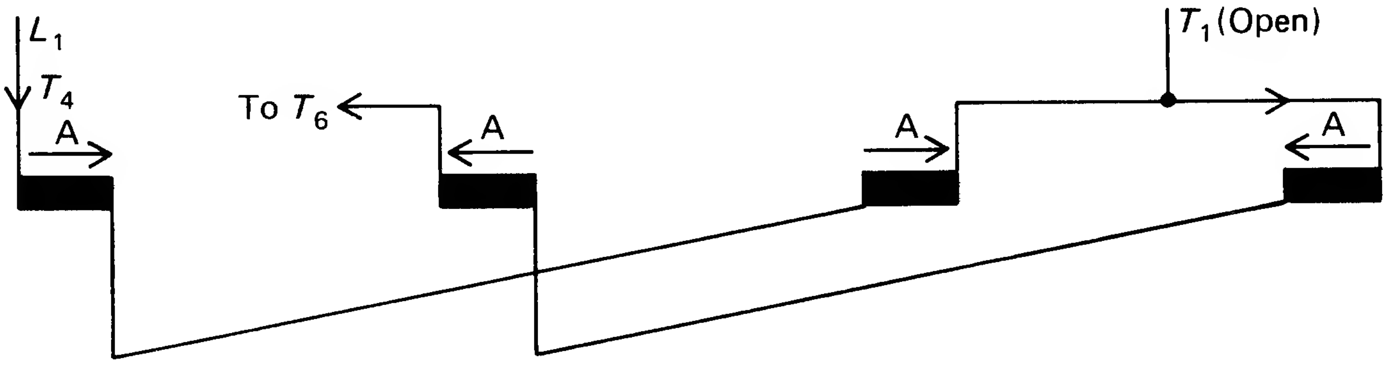


Fig. 3-133a. Phase *A* of a constant-horsepower motor, connected one delta and four pole, for high speed.

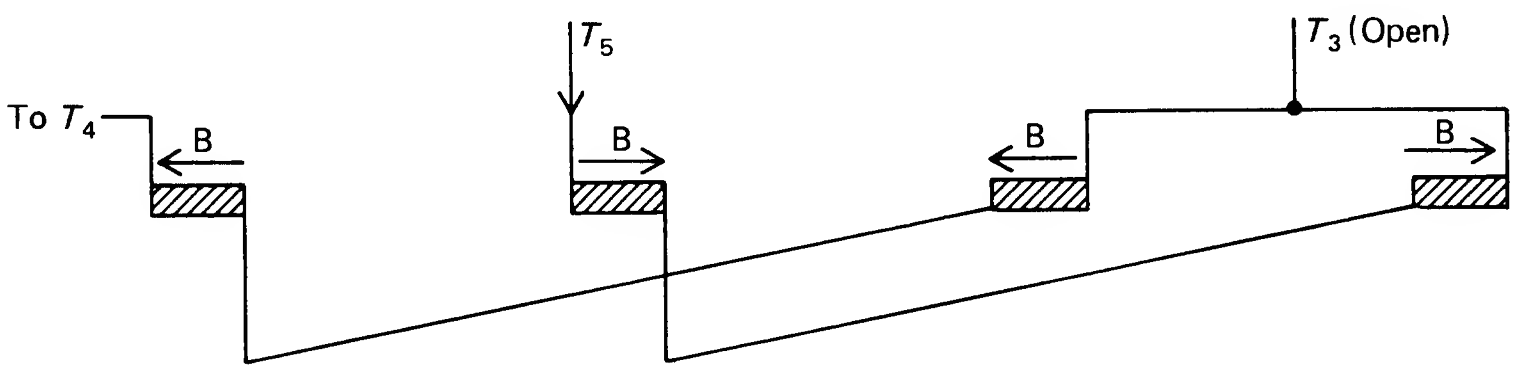


Fig. 3-133b. Phase *B* of a constant-horsepower motor, connected one delta for high speed.

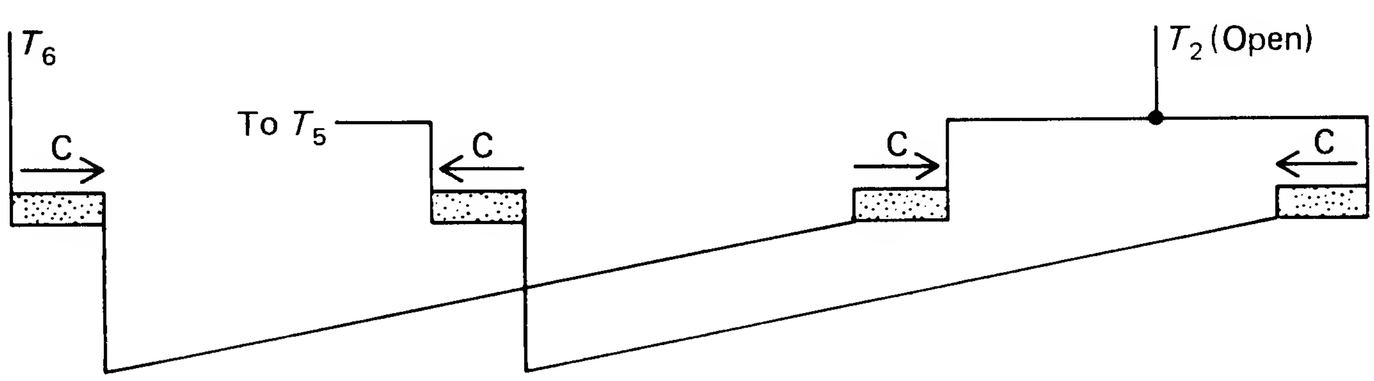


Fig. 3-133c. Phase *C* of a constant-horsepower motor, connected one delta for high speed.

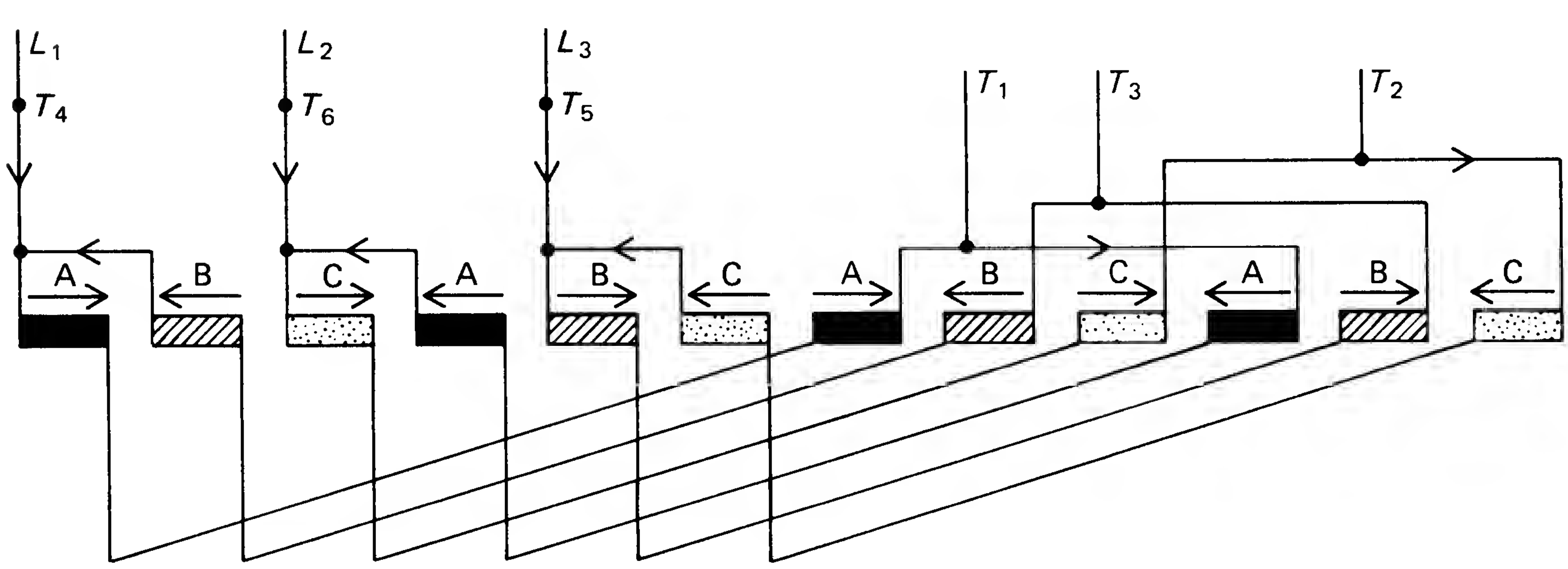


Fig. 3-133d. A four- and eight-pole constant-horsepower motor, connected one delta for high speed. T_1, T_2, and T_3 are separately insulated for this connection.

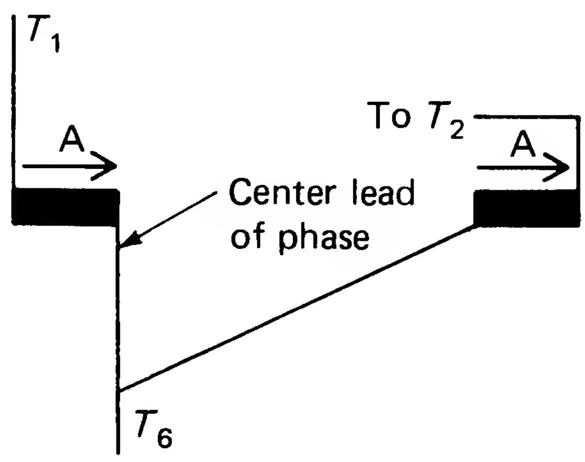


Fig. 3–134a. A two- and four-pole, constant-torque motor. The center lead connects to the left lead of the remaining group, making it the same polarity. This doubles the poles, making the one-delta connection for low speed with four poles.

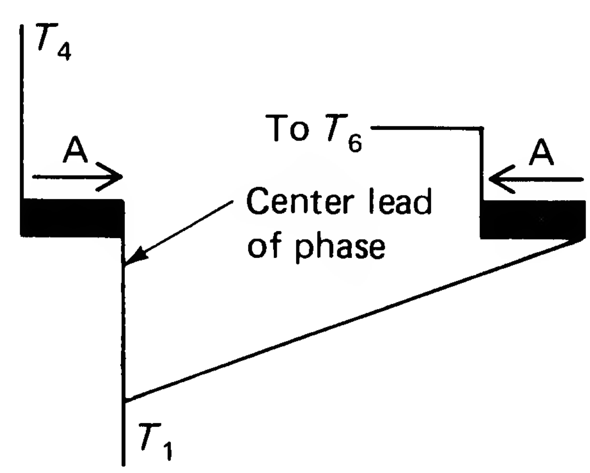


Fig. 3–134b. A two- and four-pole, constant-horsepower motor. The center lead connects to the right lead of the remaining group, making it the opposite polarity. When this connection is one delta, the motor will be for high speed with two poles.

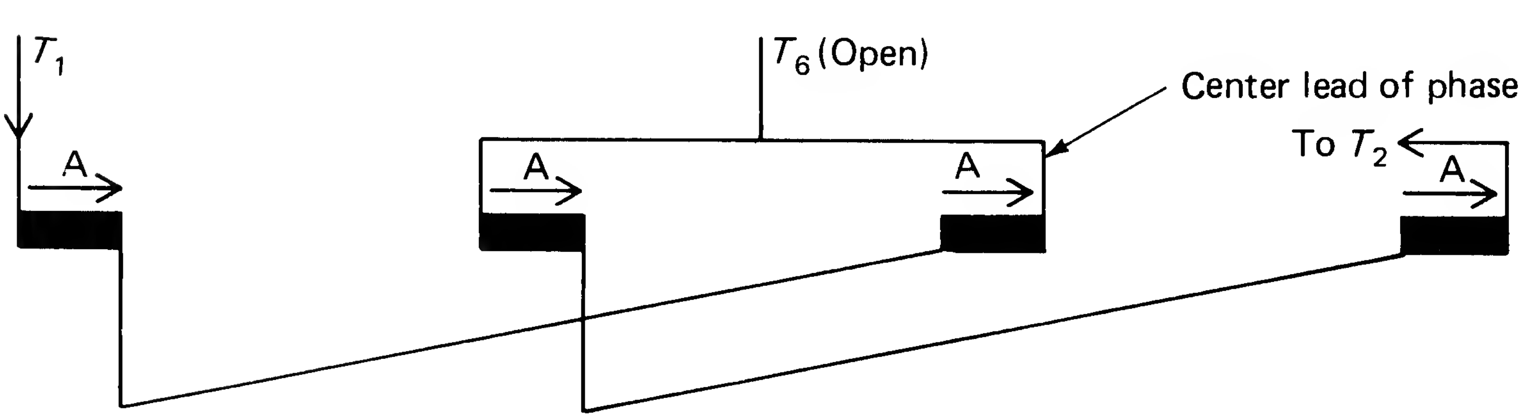


Fig. 3–135a. Phase A of a constant-torque motor. The center lead connects to the group to the left or back to the group adjacent to the starting group of the phase. When this four- and eight-pole connection is one delta, it will have eight poles.

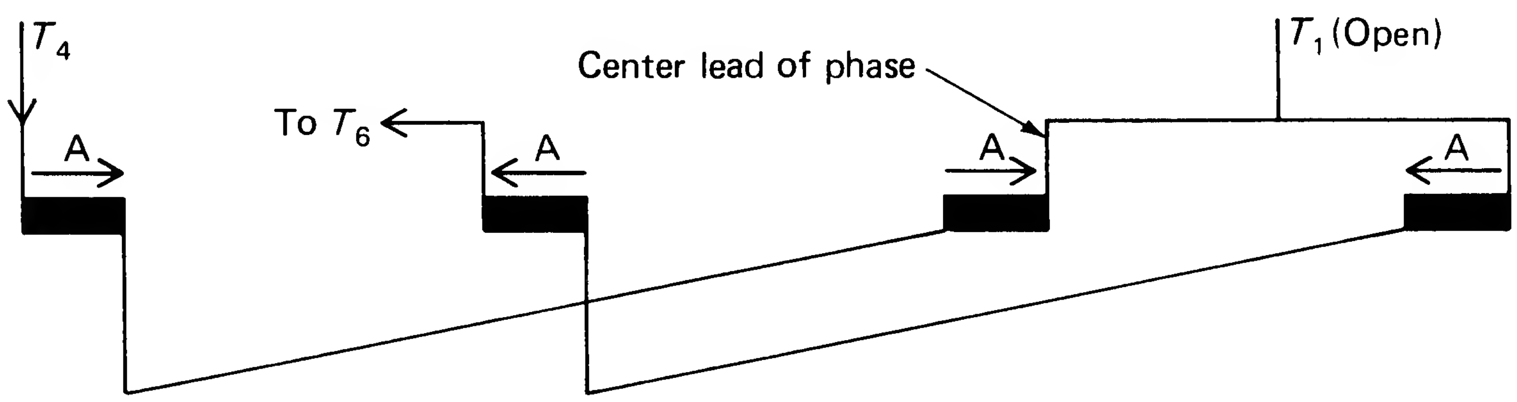


Fig. 3–135b. Phase *A* of a constant-horsepower motor. The center lead connects to the adjacent group to the right, as it would with a normal long jumper motor. When this four- and eight-pole connection is one delta, it will have four poles.

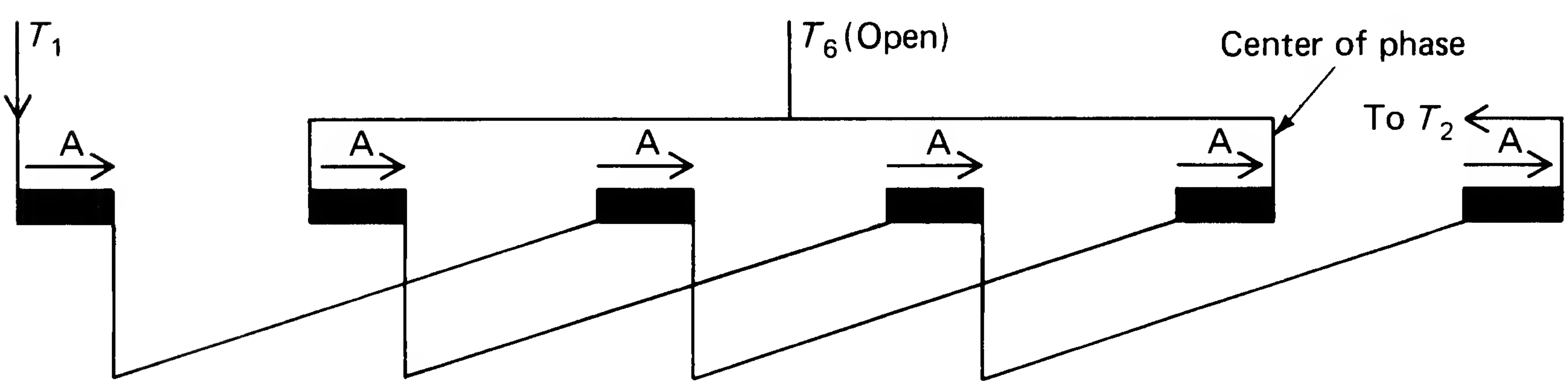


Fig. 3–136a. A six- and 12-pole, constant-torque motor. The center lead connects to the left lead of the group adjacent to the group that is the start of the phase. When this six- and 12-pole motor is connected as one delta, it will have 12 poles.

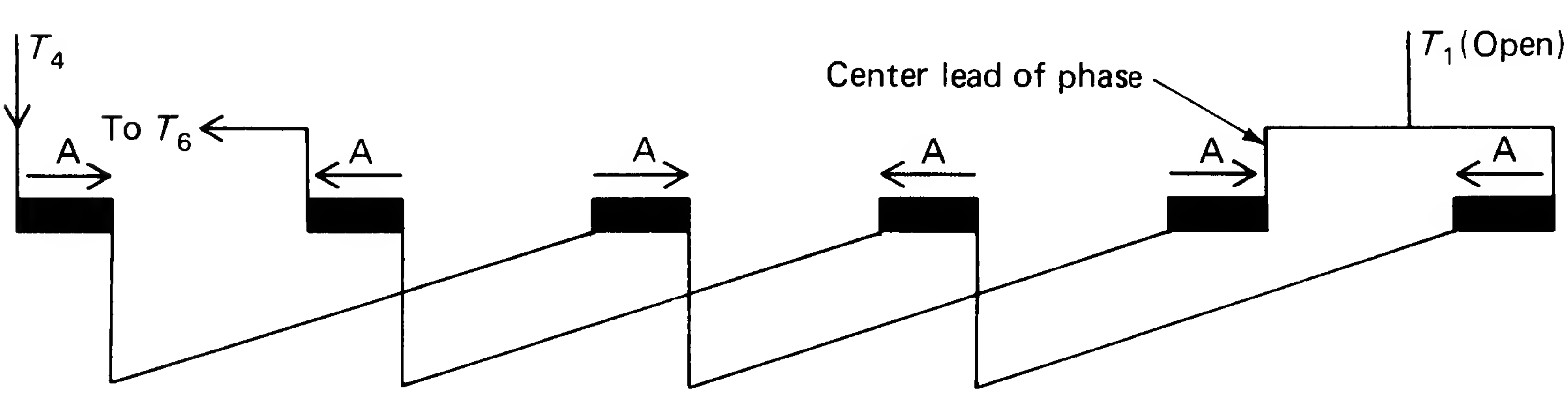


Fig. 3–136b. A six- and 12-pole, constant-horsepower motor. The center lead connects to the right lead of the group adjacent to it, the same as a normal delta motor is. Connected as one delta, this six- and 12-pole motor will have 12 poles.

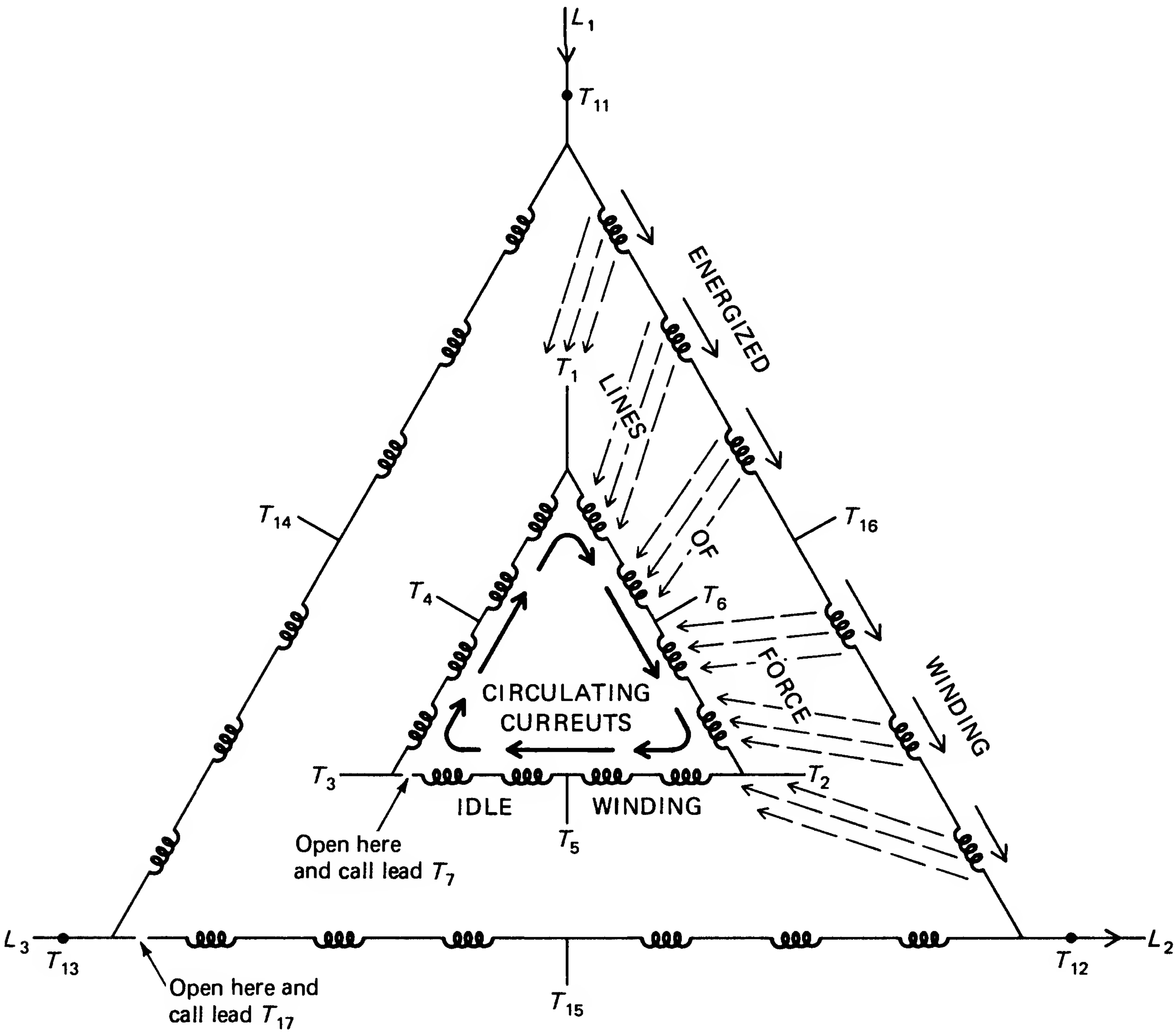


Fig. 3–137. A four-speed constant-torque motor consisting of a four- and eight-pole winding and a six- and 12-pole winding. The idle winding must be opened to prevent circulating currents induced from the energized winding.

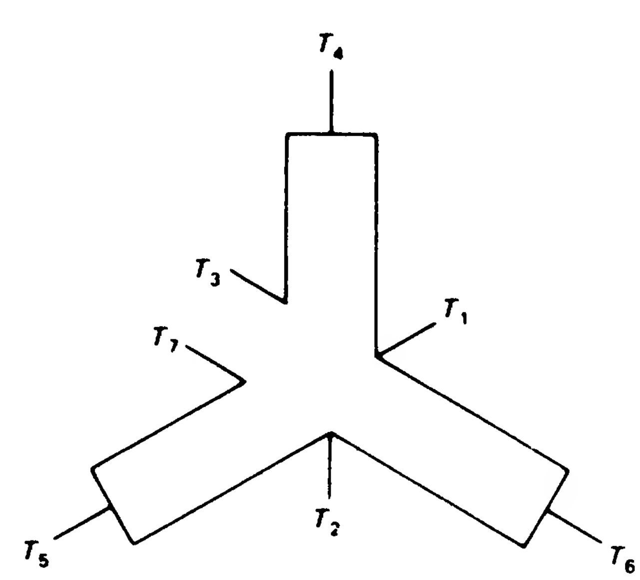


Fig. 3–138. Two-speed seven-lead motor. Constant torque.

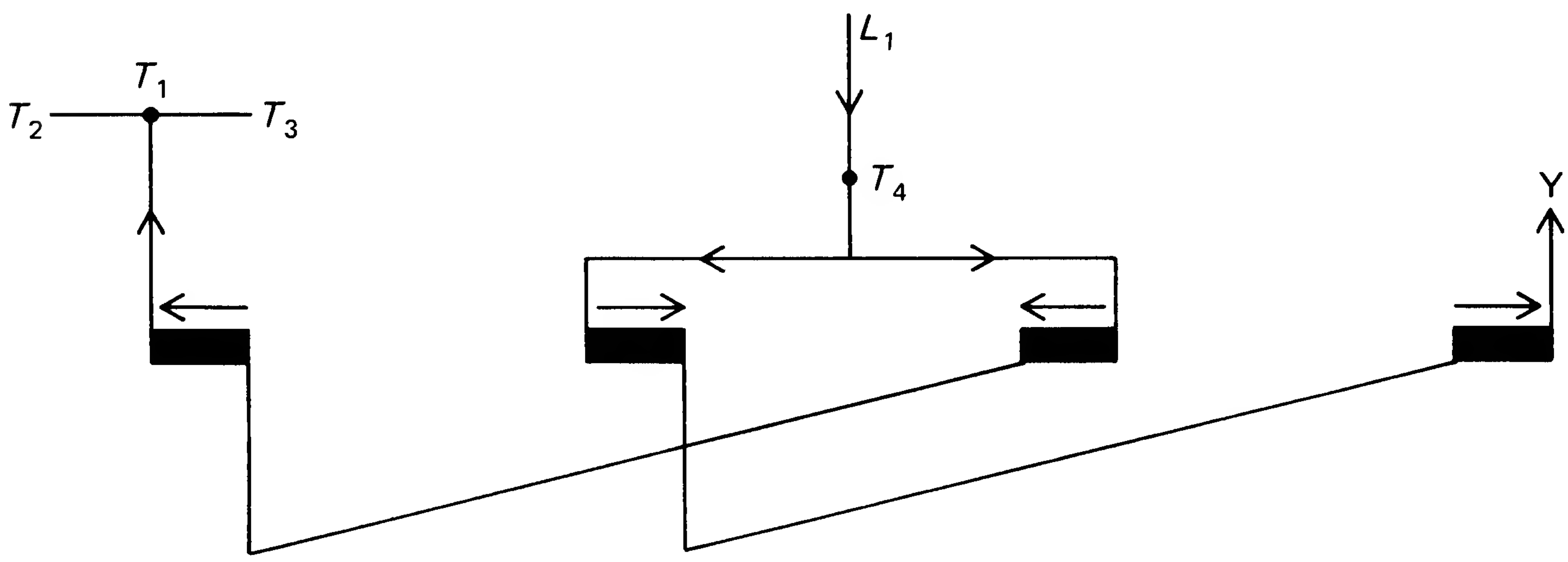


Fig. 3-139. Phase *A* of a variable-torque motor connected two wye for high speed.

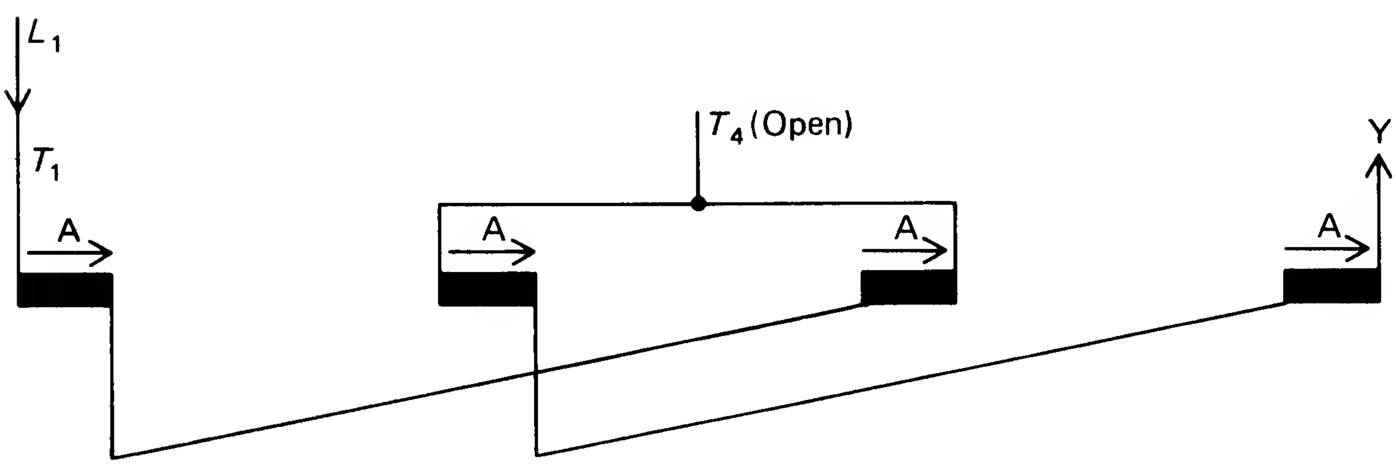


Fig. 3-140a. Phase *A* of a variable-torque motor connected one wye for low speed.

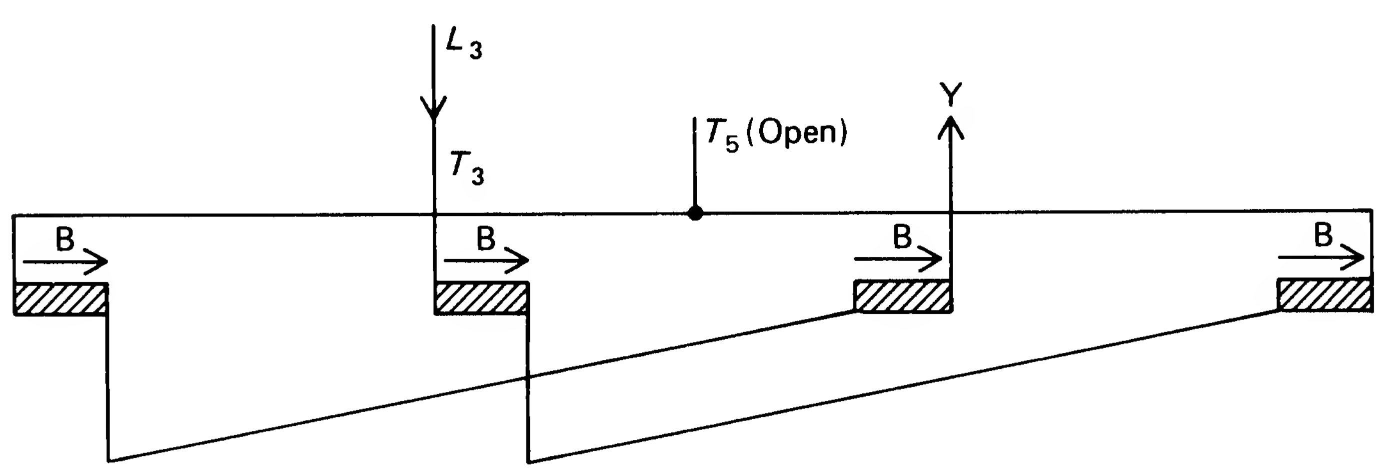


Fig. 3-140b. Phase *B* of a variable-torque motor connected one wye for low speed.

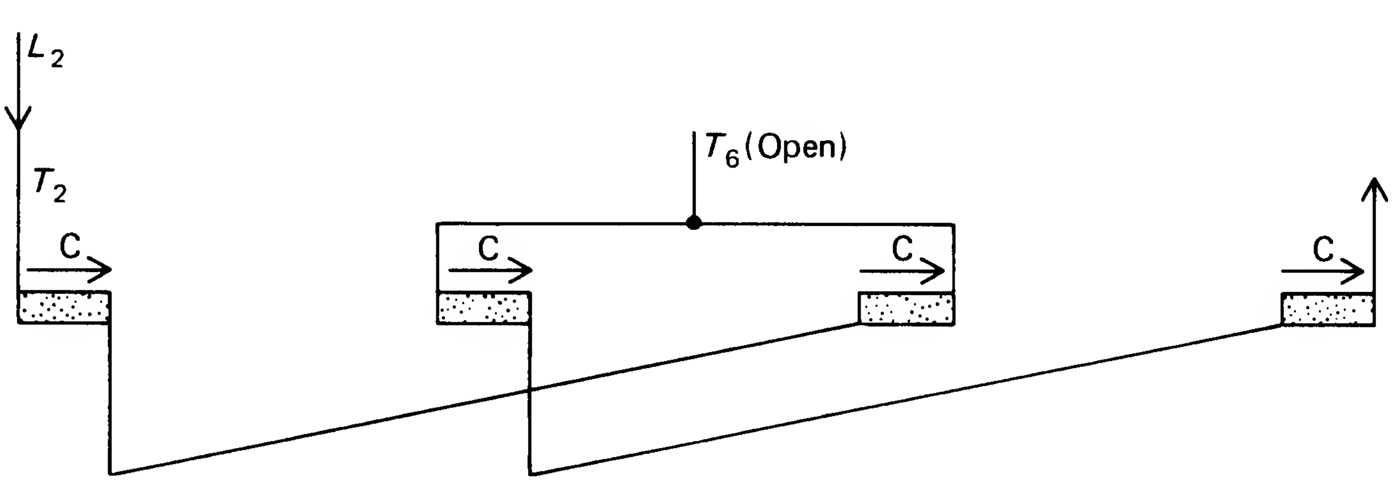


Fig. 3-140c. Phase *C* of a variable-torque motor connected one wye for low speed.

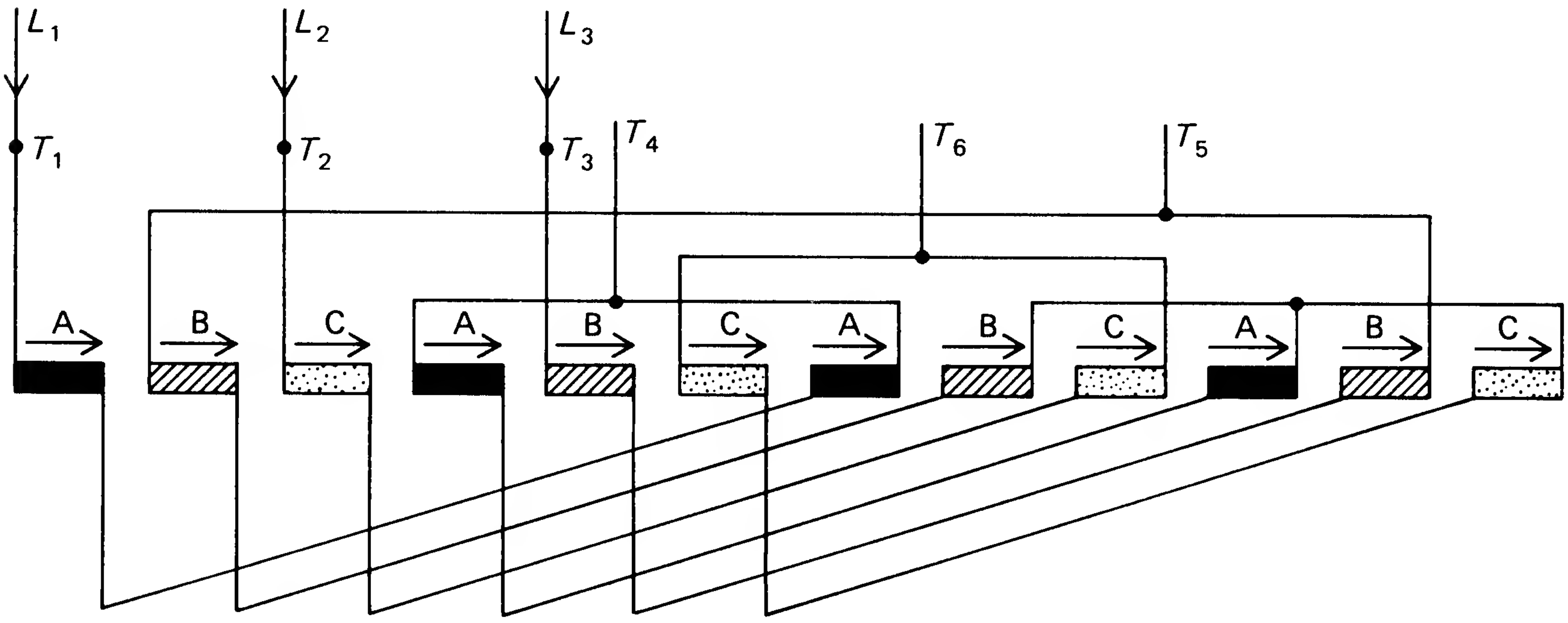
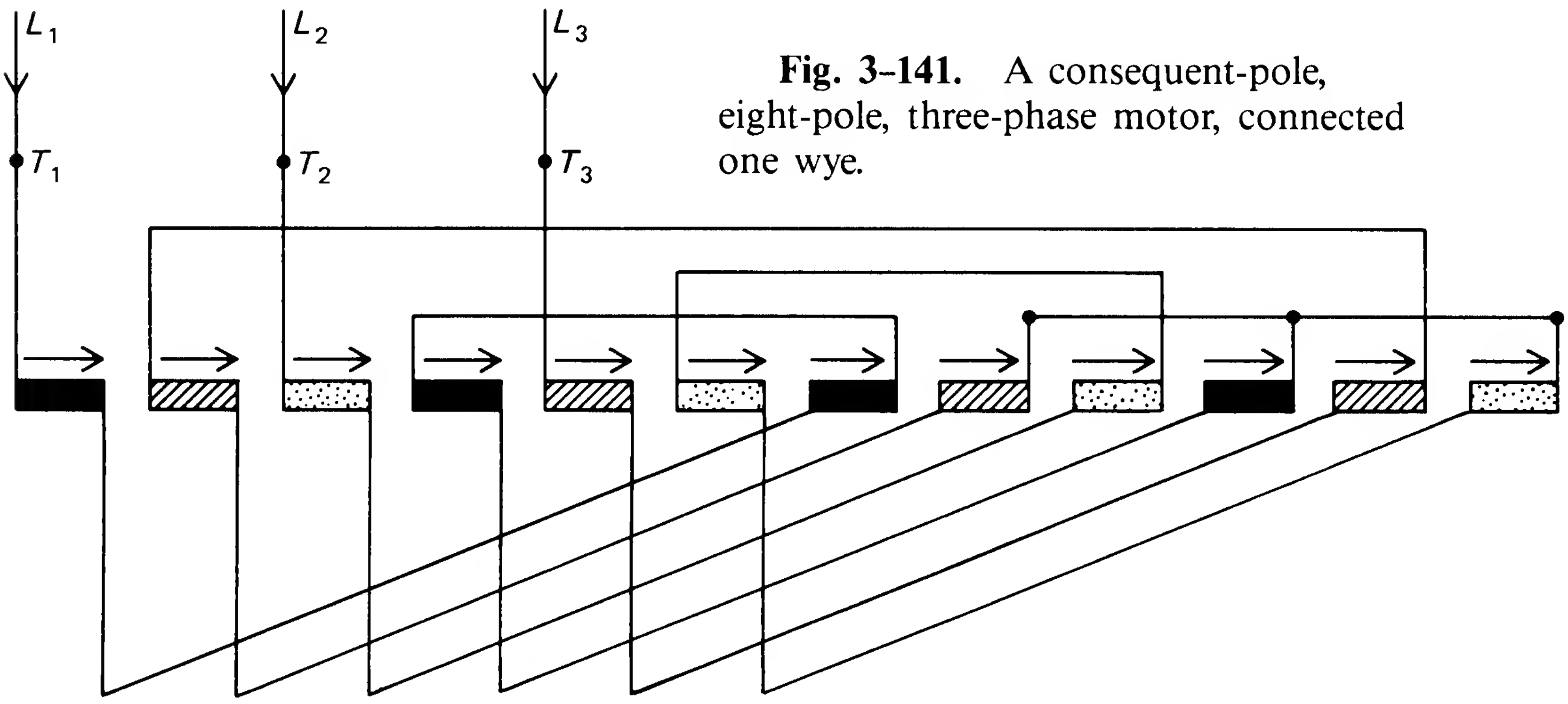


Fig. 3-140d. A variable-torque four- and eight-pole motor connected one wye for eight poles and low speed. For high speed, connect L_1 to T_4, L_2 to T_6, L_3 to T_5, and connect T_1, T_2, and T_3 together.

Fig. 3-141. A consequent-pole, eight-pole, three-phase motor, connected one wye.



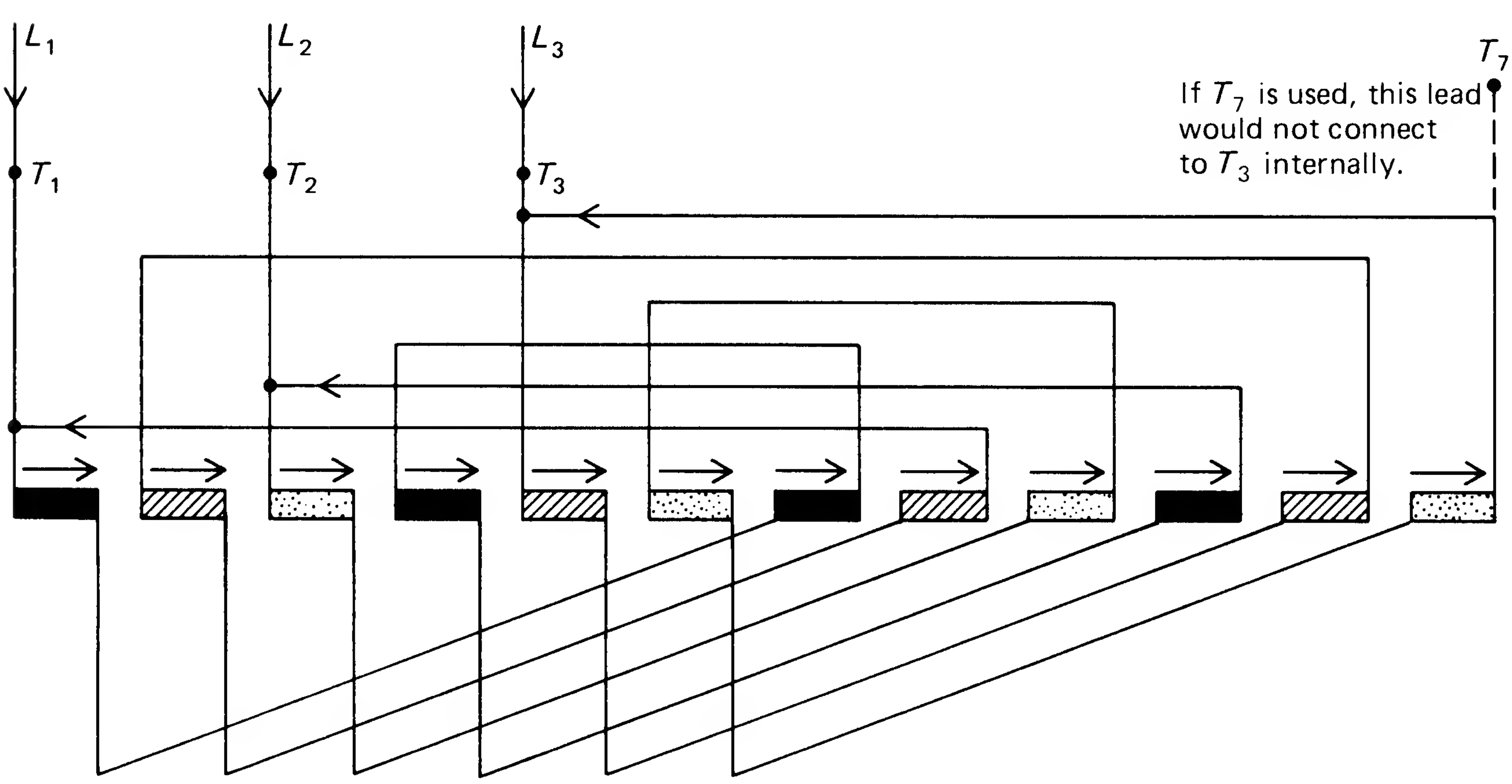
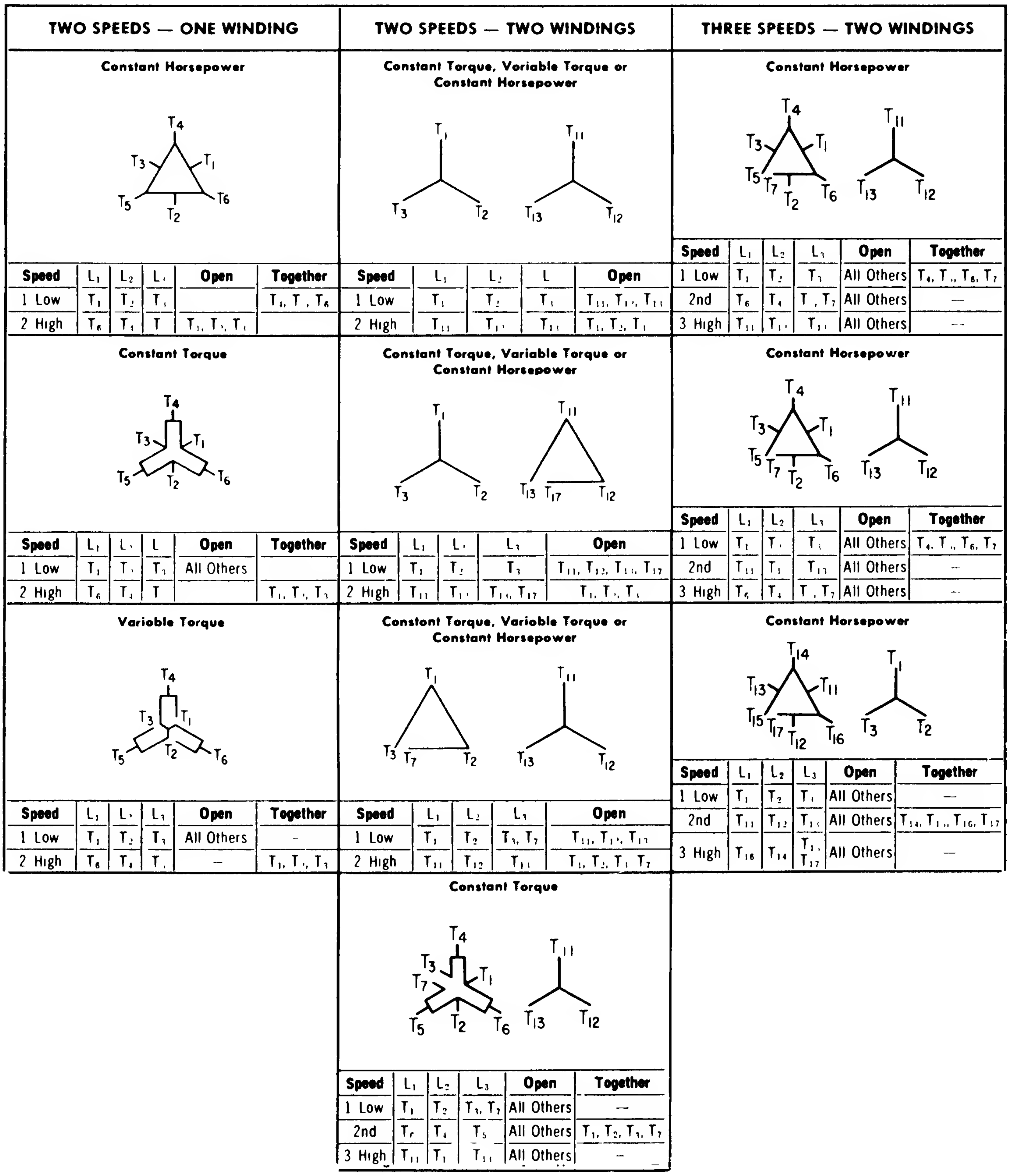


Fig. 3-142. A consequent-pole, eight-pole, three-phase motor, connected one delta. T_7 is used instead of connecting to T_3 when this connection is used in a two-winding motor.



Two Speeds — One Winding: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3		T_4, T_5, T_6
2 High	T_6	T_4	T_5	T_1, T_2, T_3	

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower

Speed	L_1	L_2	L_3	Open
1 Low	T_1	T_2	T_3	T_{11}, T_{12}, T_{13}
2 High	T_{11}	T_{12}	T_{13}	T_1, T_2, T_3

Three Speeds — Two Windings: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	T_4, T_5, T_6, T_7
2nd	T_6	T_4	T_5, T_7	All Others	—
3 High	T_{11}	T_{12}	T_{13}	All Others	—

Two Speeds — One Winding: Constant Torque

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	
2 High	T_6	T_4	T_5		T_1, T_2, T_3

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower

Speed	L_1	L_2	L_3	Open
1 Low	T_1	T_2	T_3	$T_{11}, T_{12}, T_{13}, T_{17}$
2 High	T_{11}	T_{12}	T_{13}, T_{17}	T_1, T_2, T_3

Three Speeds — Two Windings: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	T_4, T_5, T_6, T_7
2nd	T_{11}	T_{12}	T_{13}	All Others	—
3 High	T_6	T_4	T_5, T_7	All Others	—

Two Speeds — One Winding: Variable Torque

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	-
2 High	T_6	T_4	T_5	—	T_1, T_2, T_3

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower

Speed	L_1	L_2	L_3	Open
1 Low	T_1	T_2	T_3, T_7	T_{11}, T_{12}, T_{13}
2 High	T_{11}	T_{12}	T_{13}	T_1, T_2, T_3, T_7

Three Speeds — Two Windings: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	—
2nd	T_{11}	T_{12}	T_{13}	All Others	$T_{14}, T_{15}, T_{16}, T_{17}$
3 High	T_{16}	T_{14}	T_{15}, T_{17}	All Others	—

Three Speeds — Two Windings: Constant Torque

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3, T_7	All Others	—
2nd	T_6	T_4	T_5	All Others	T_1, T_2, T_3, T_7
3 High	T_{11}	T_{12}	T_{13}	All Others	—

Fig. 3–143. Connections for multispeed squirrel cage motors. *(Allen-Bradley Co.)*

First half									Second half								
1			2			3			1			2			3		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S
2	3	3	3	3	2	3	2	3	2	3	3	3	3	2	3	2	3

Fig. 3–144. The odd-pole group distribution of a six-pole, 48-slot motor.

First half						Second half						
1			2			1			2			
A	B	C	A	B	C	A	B	C	A	B	C	
N	S	N	S	N	S	N	S	N	S	N	S	
5	4	5	4	5	4	5	4	5	4	5	4	— short jumper
5	4	5	4	5	4	4	5	4	5	4	5	— long jumper

Fig. 3–145. Distribution of a four-pole, 54-slot motor showing both short jumper and long jumper arrangements.

First half						Second half						
1			2			1			2			
A	B	C	A	B	C	A	B	C	A	B	C	
N	S	N	S	N	S	N	S	N	S	N	S	
7	6X	7	6	7	6	7	X6	7	6	7	6	— short jumper
7	6X	7	6	7	6	6X	7	6	7	6	7	— long jumper

Fig. 3–146. Distribution of a four-pole, 80-slot motor showing both short and long jumper arrangments. The X indicates a dead coil location.

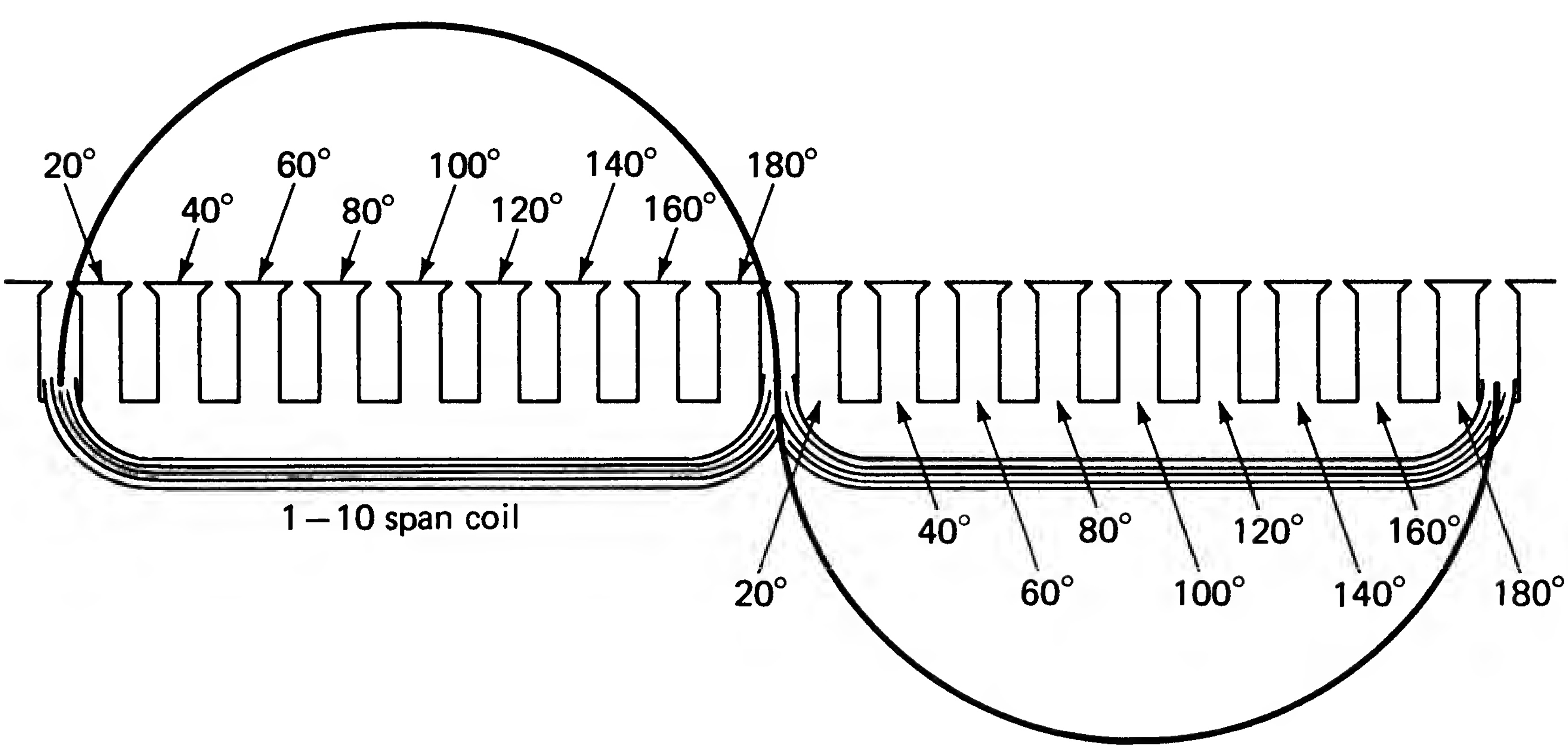


Fig. 3–147. The sine wave as it would compare with two full spanned coils in the flattened slots of a four-pole, 36-slot stator. One tooth = 20°.

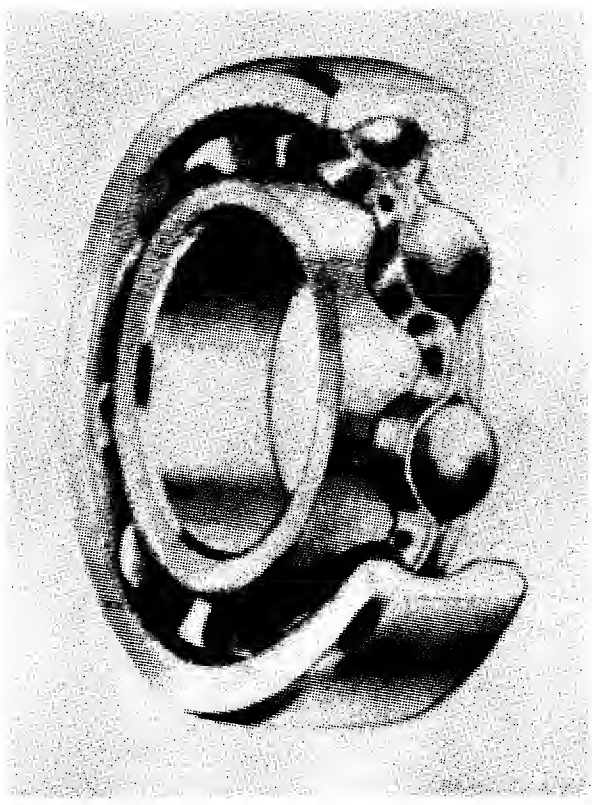


Fig. 3-148. A ball-bearing illustration showing the components. (*SNR*)

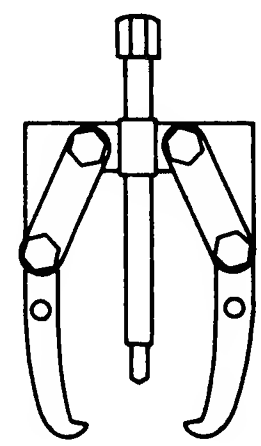


Fig. 3-149. One style of bearing puller.

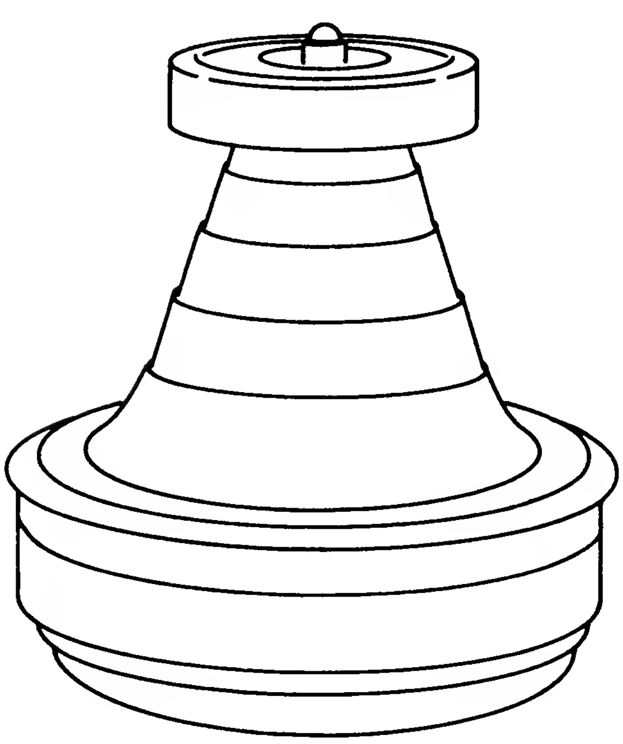


Fig. 3-150. A ball-bearing heater used to install ball bearings.

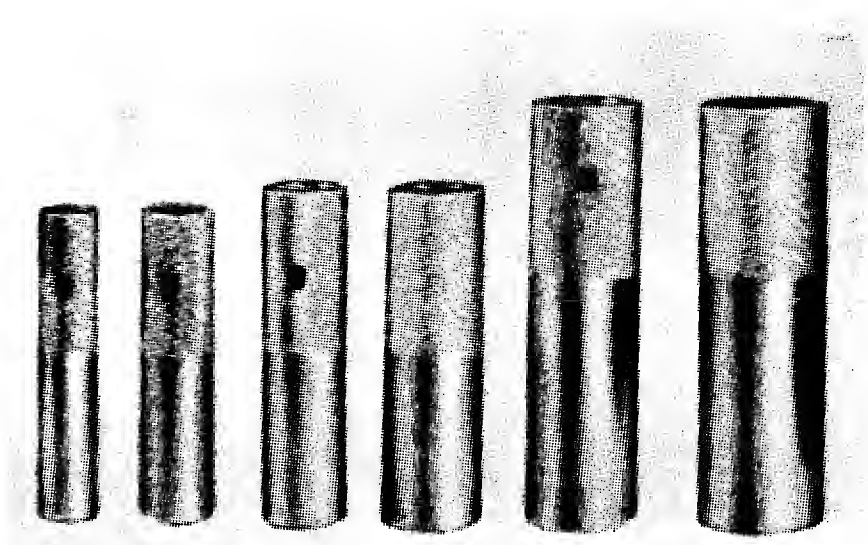


Fig. 3-151. Tubes made for driving or pressing ball bearings onto the shaft of an electric motor.

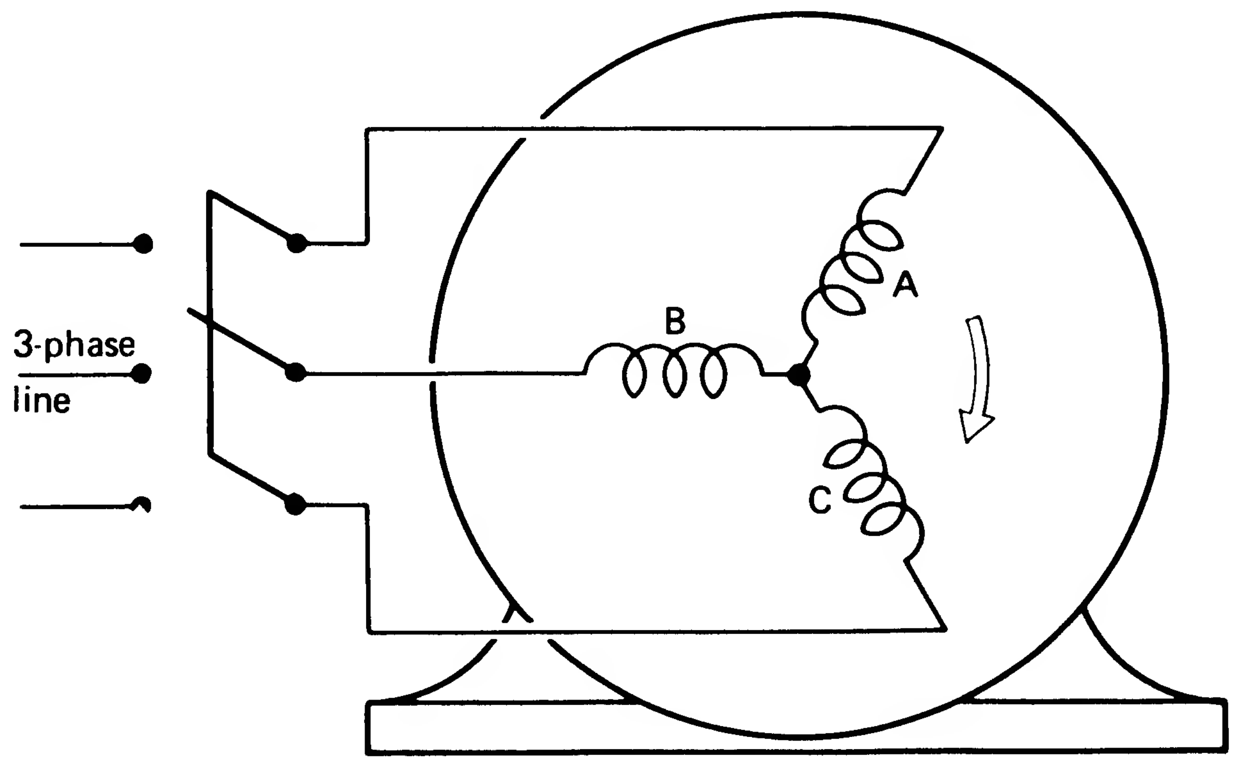


Fig. 3-152. A three-phase motor connected to a three-phase line.

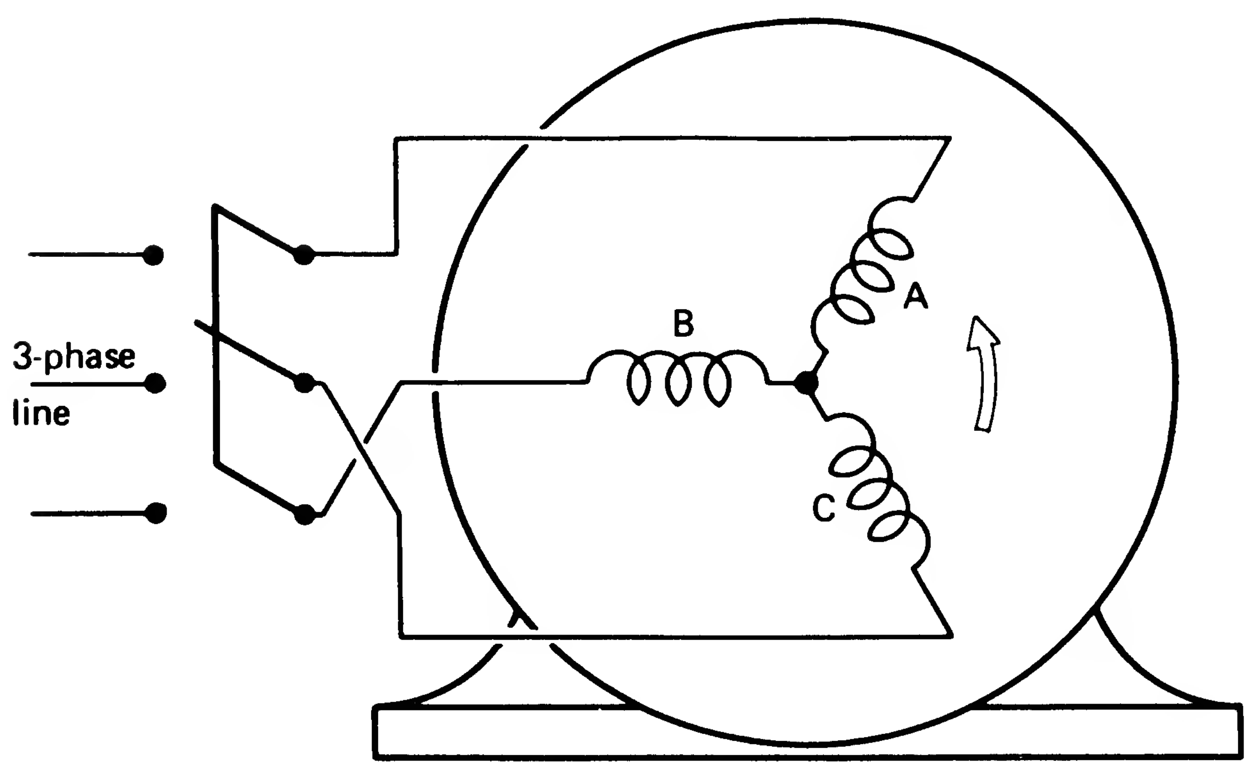


Fig. 3-153. To reverse the direction of rotation, interchange any two motor leads.

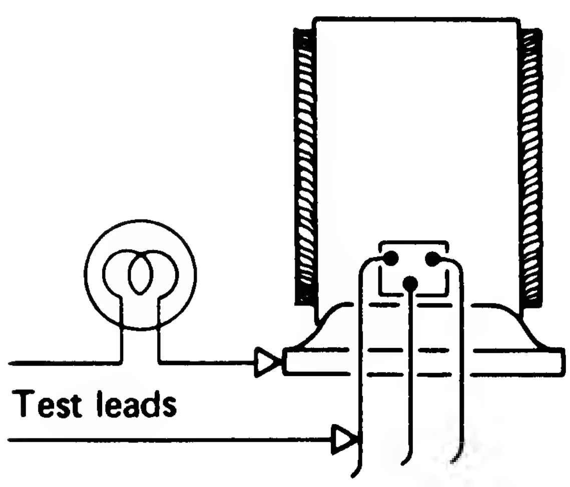


Fig. 3-154. Testing a polyphase motor for grounds.

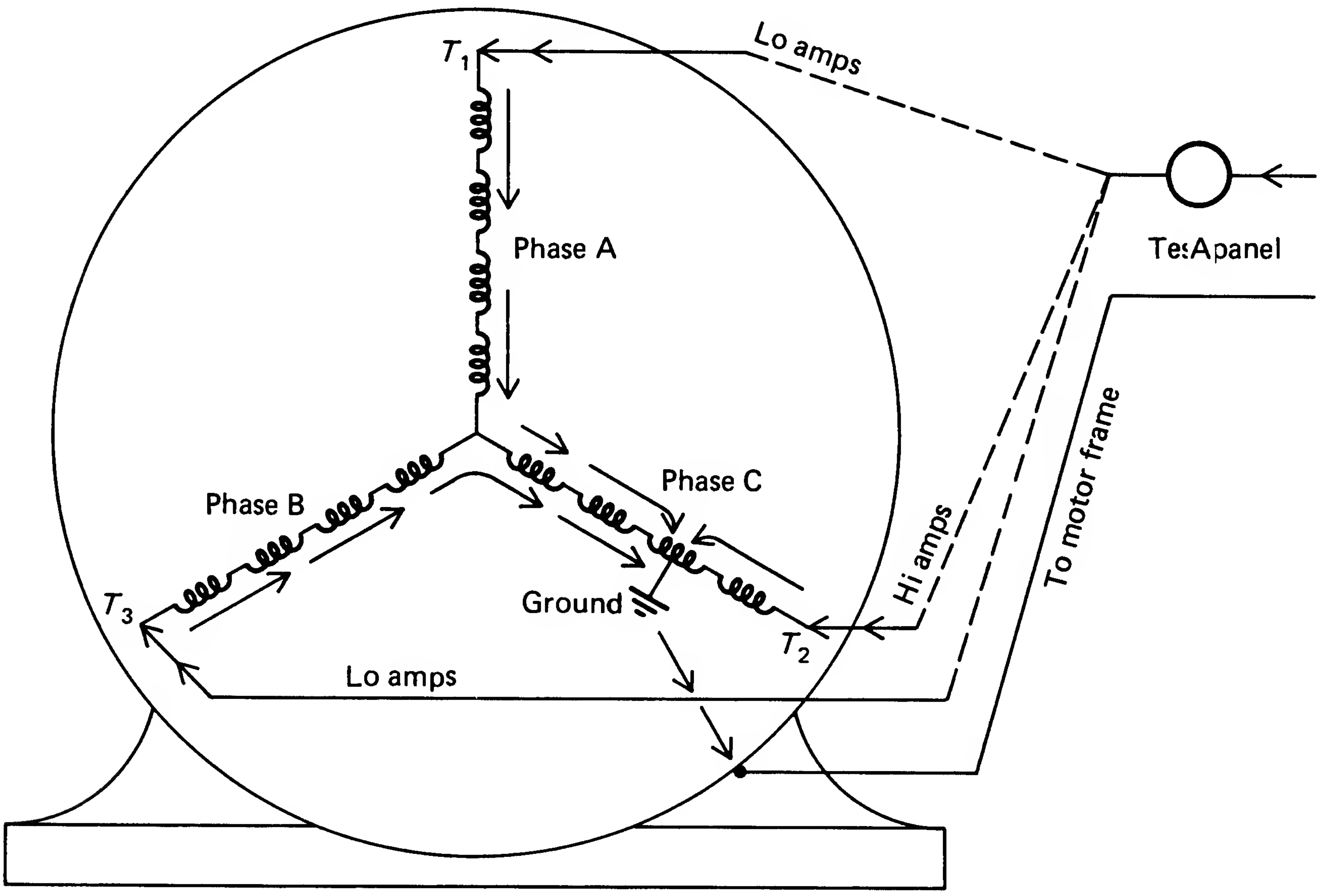


Fig. 3-155. Testing a series-wye motor to locate the grounded phase. T_2 has the highest amp reading, showing the *C* phase to be grounded.

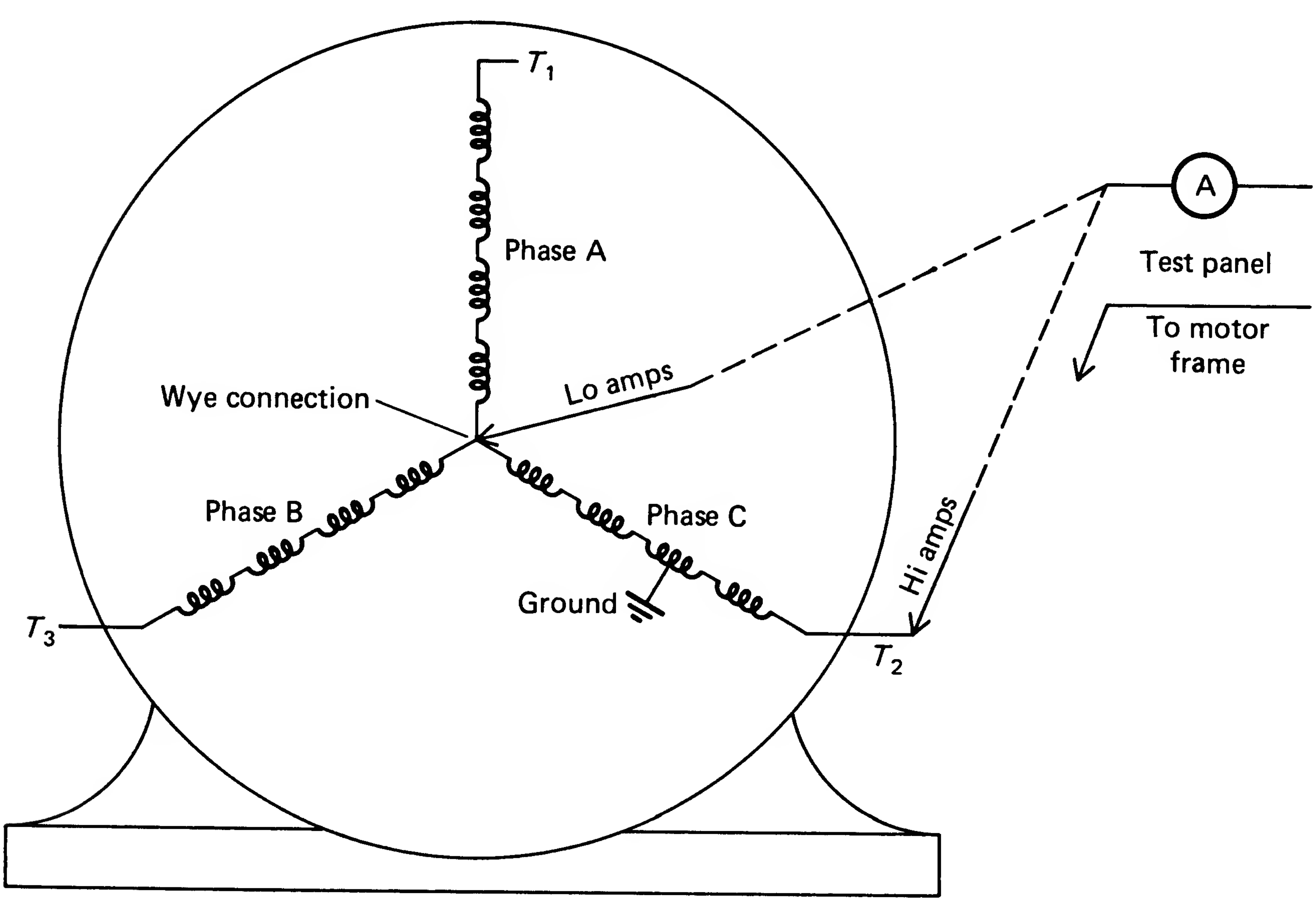


Fig. 3-156. Testing the *C* phase of a series-wye-connected motor to locate the end closer to the grounded coil.

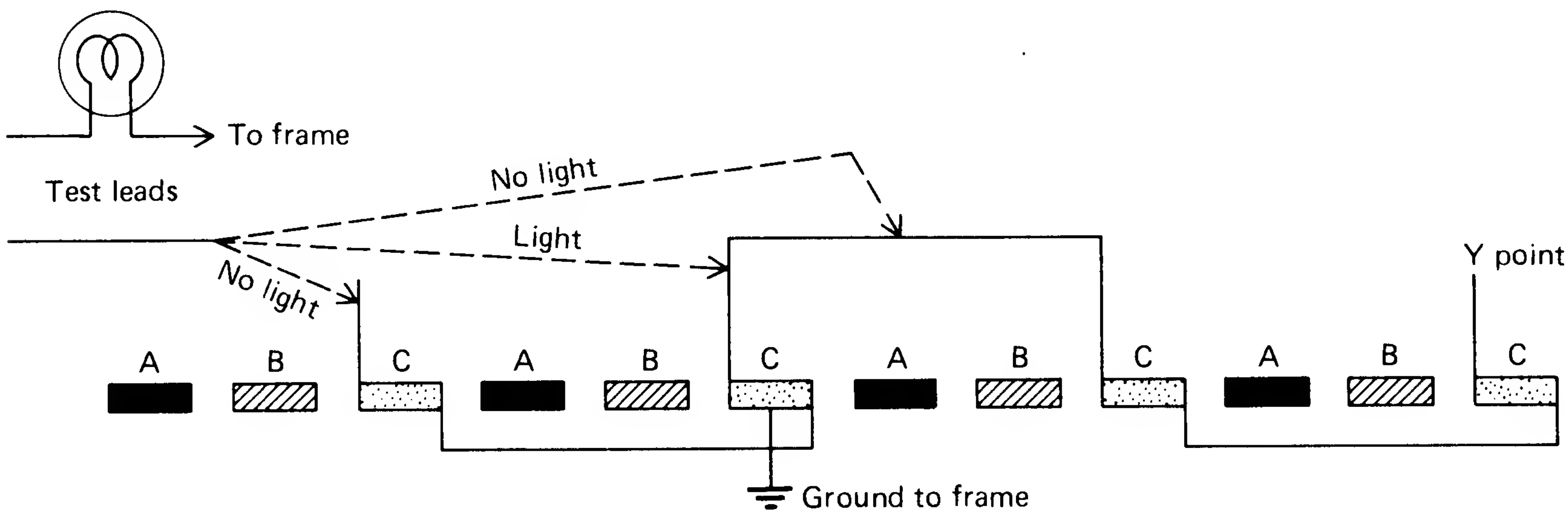


Fig. 3–157. Locating the grounded group with a test light by opening splices.

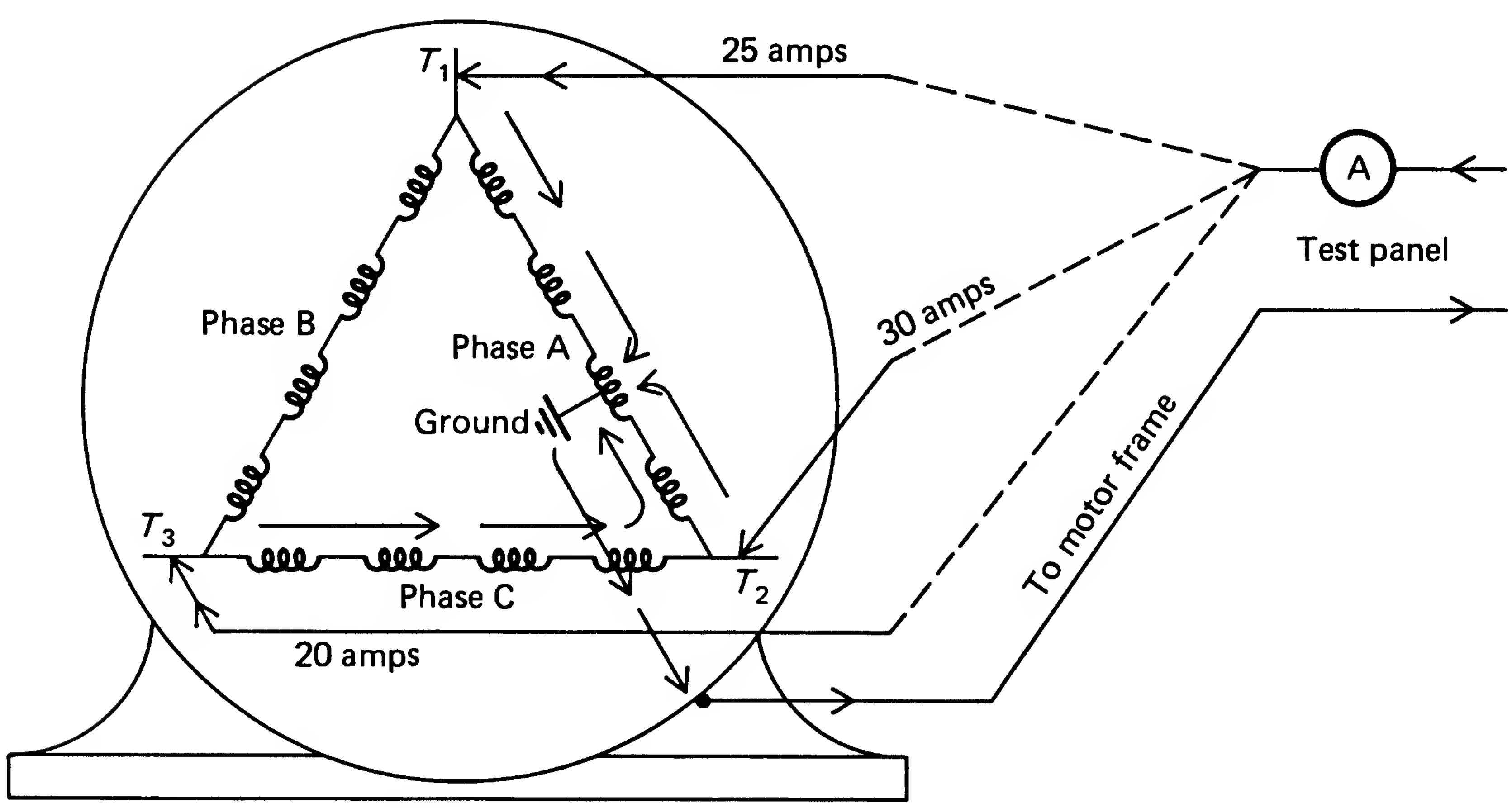


Fig. 3–158. Testing a series-delta motor to locate the grounded phase. T_2 has the highest amp reading, and T_1 is second highest, showing the ground to be in the A phase close to T_2.

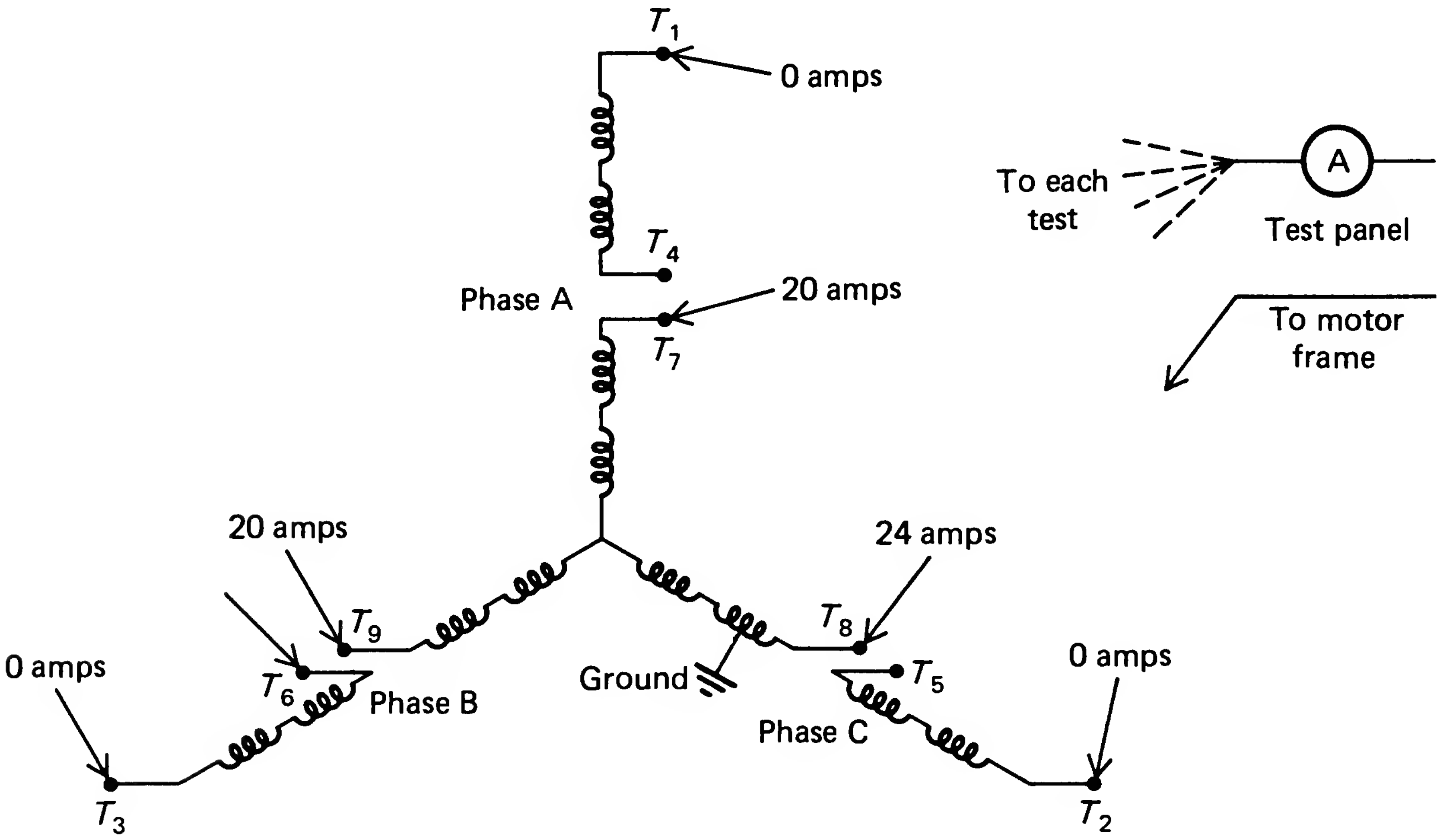


Fig. 3-159. Testing a one- and two-wye motor to locate the grounded phase. T_8 has the highest amp reading, showing the C phase to be grounded.

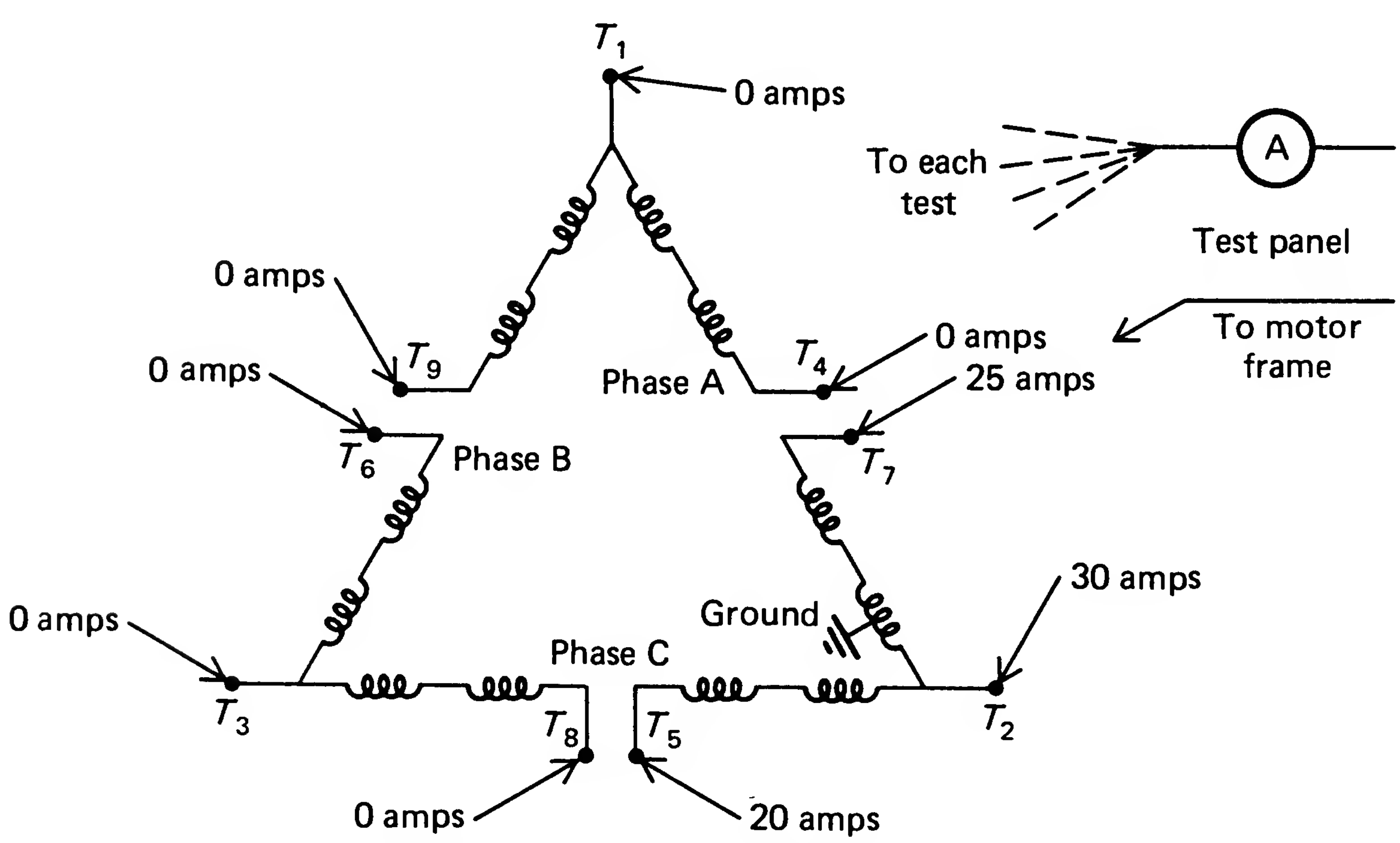


Fig. 3-160. Testing a one- and two-delta motor to locate the grounded phase. T_2 has the highest amp reading, and T_7 is second highest showing the ground to be in the A phase close to T_2.

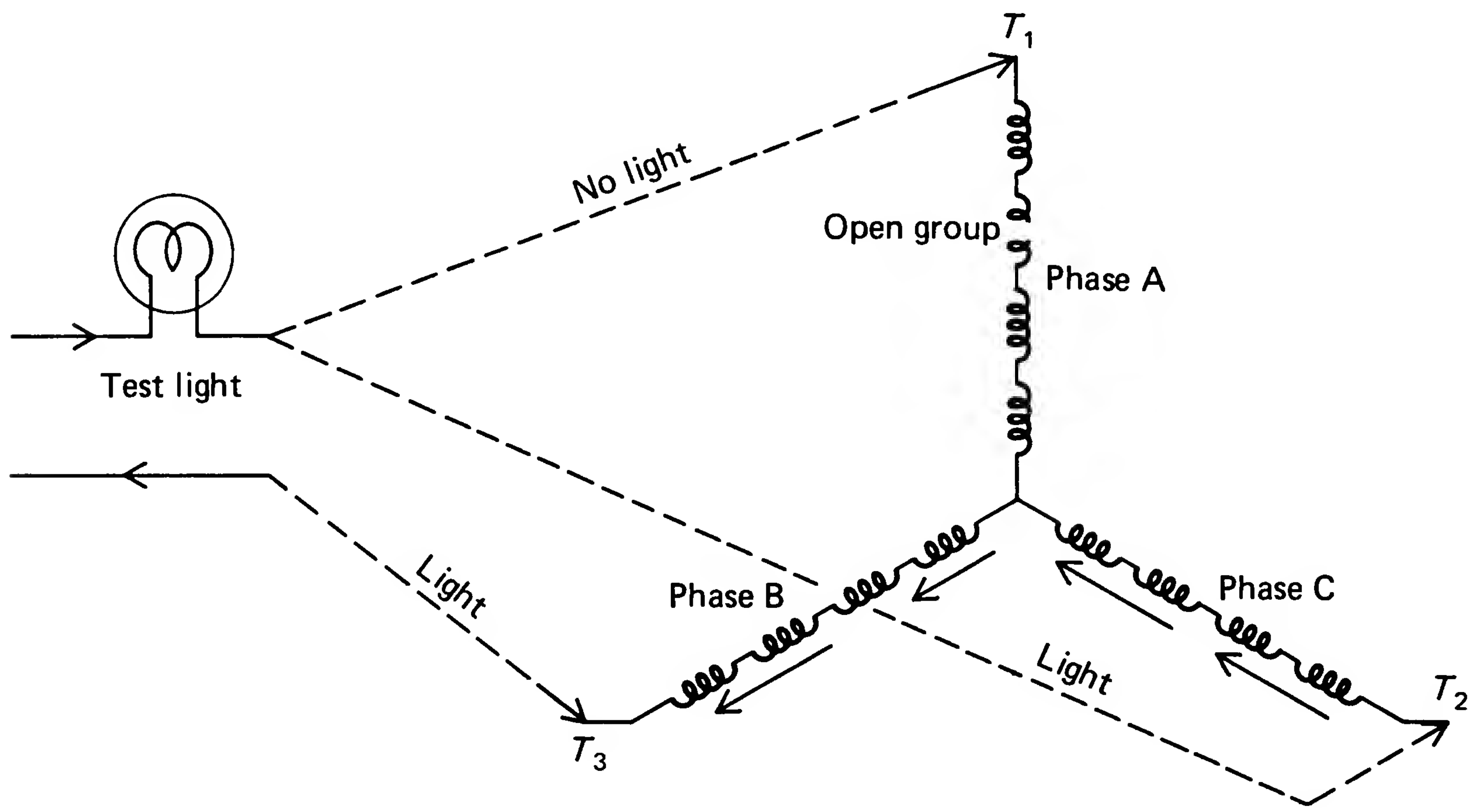


Fig. 3-161. Locating the open phase with a test light.

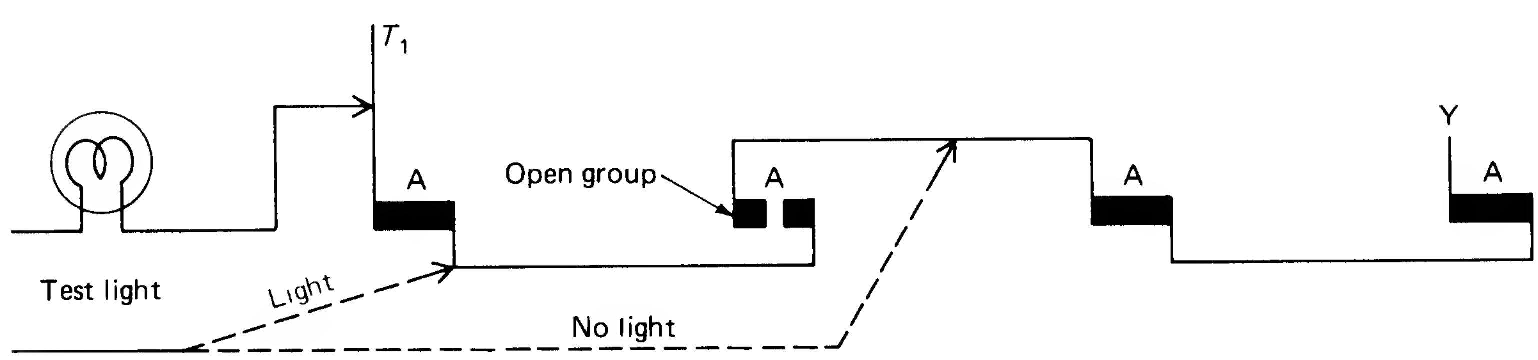


Fig. 3-162. Locating the open group with a test light.

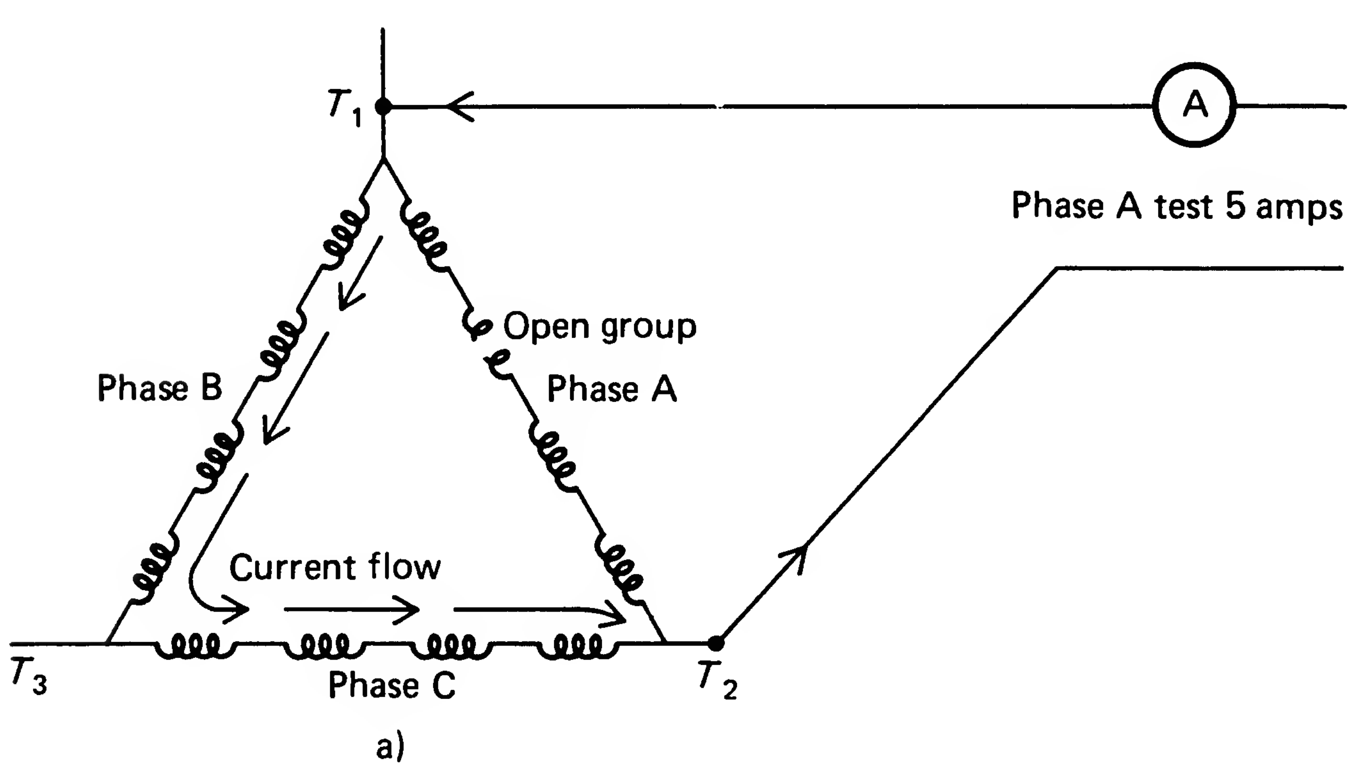


Fig. 3-163a. Using the limited current method to find the open phase in a delta connection. The open phase will have the lower amp reading.

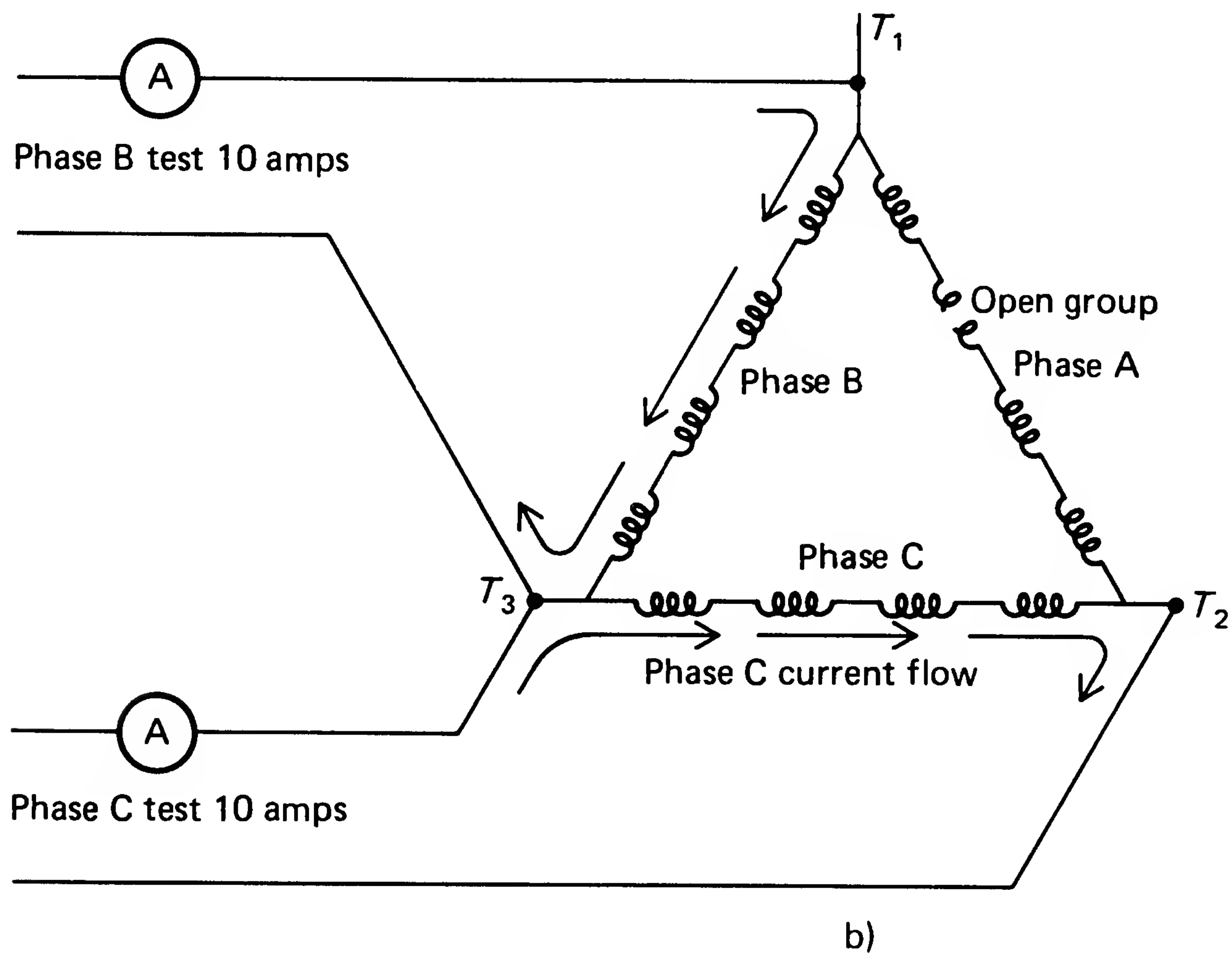


Fig. 3-163b. Using the limited current test to find the open phase of a delta-connected motor. More current will flow when testing across the good phases than across the open phase.

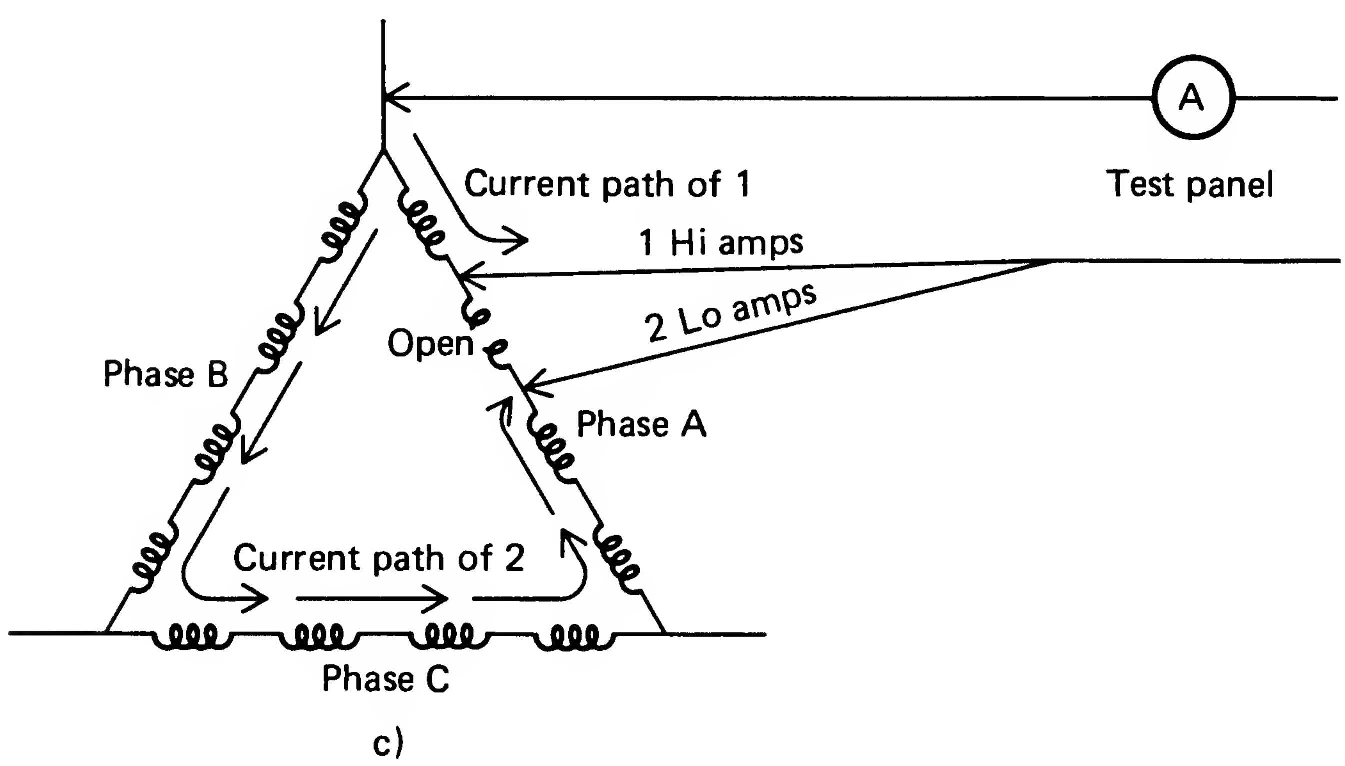


Fig. 3-163c. Locating the open group in the *A* phase of a delta-connected motor using the limited current method. The current in test 1 is high because it goes through only one group. The current in test 2 goes through most of the groups and is low.

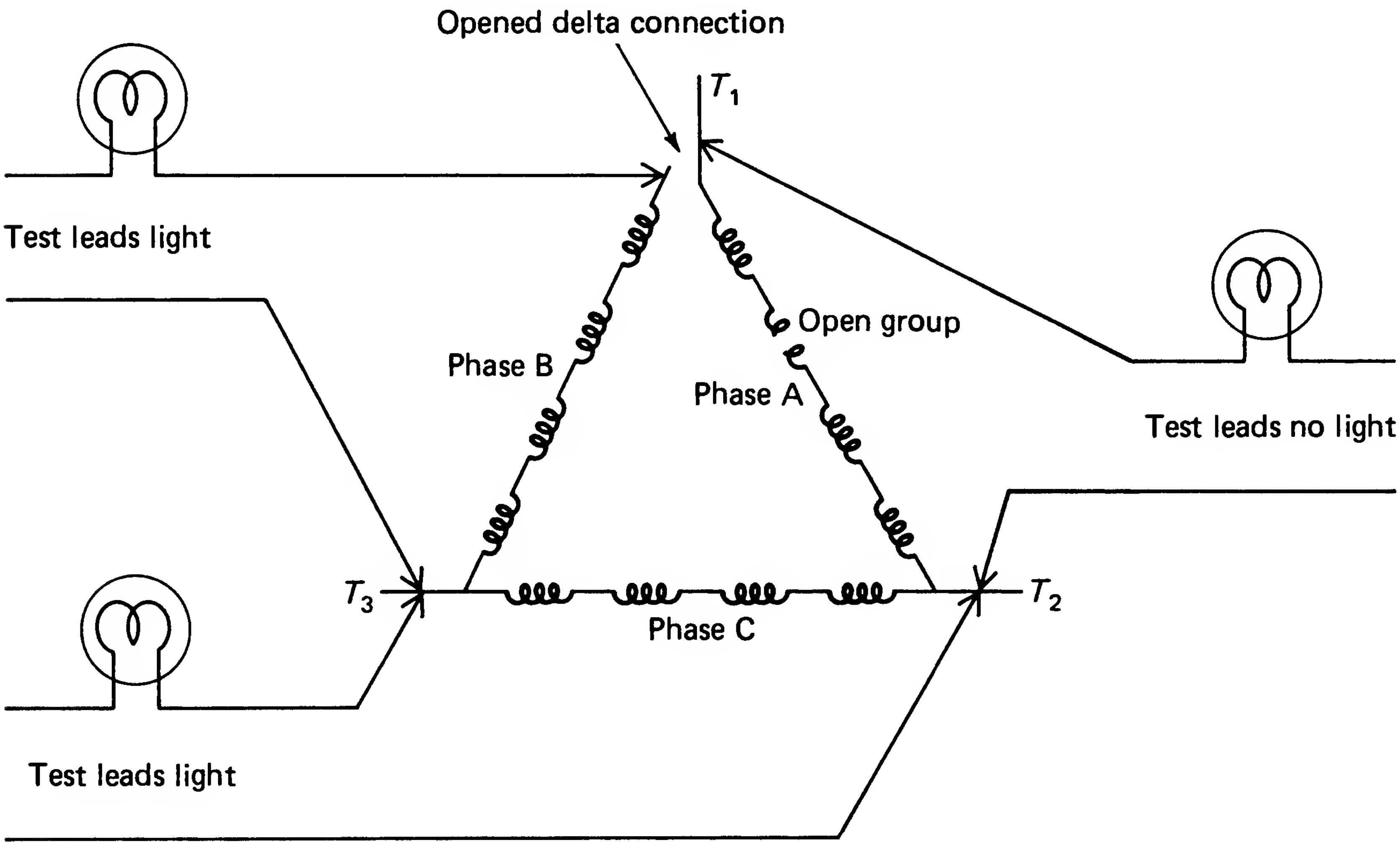


Fig. 3-164. Finding open winding with test light. Delta connection must be opened at the leads when using test light for this test.

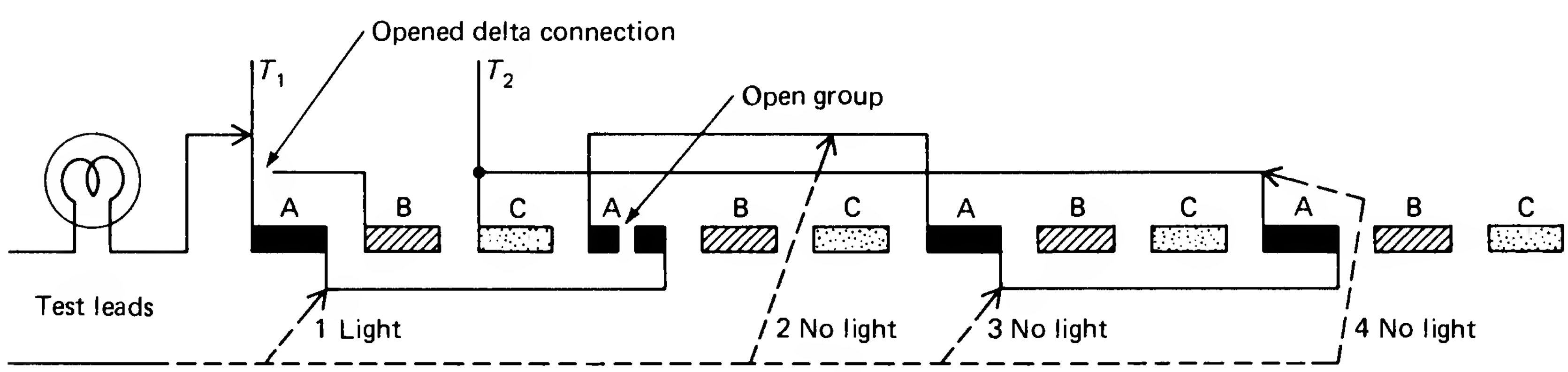


Fig. 3-165. How to find an open group with a test light on a delta connection.

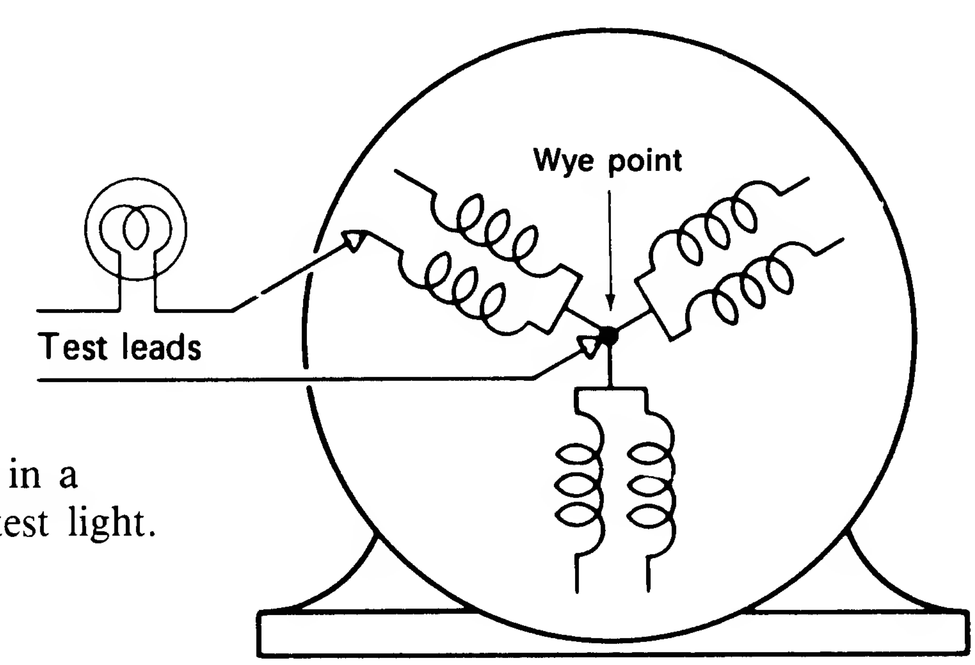
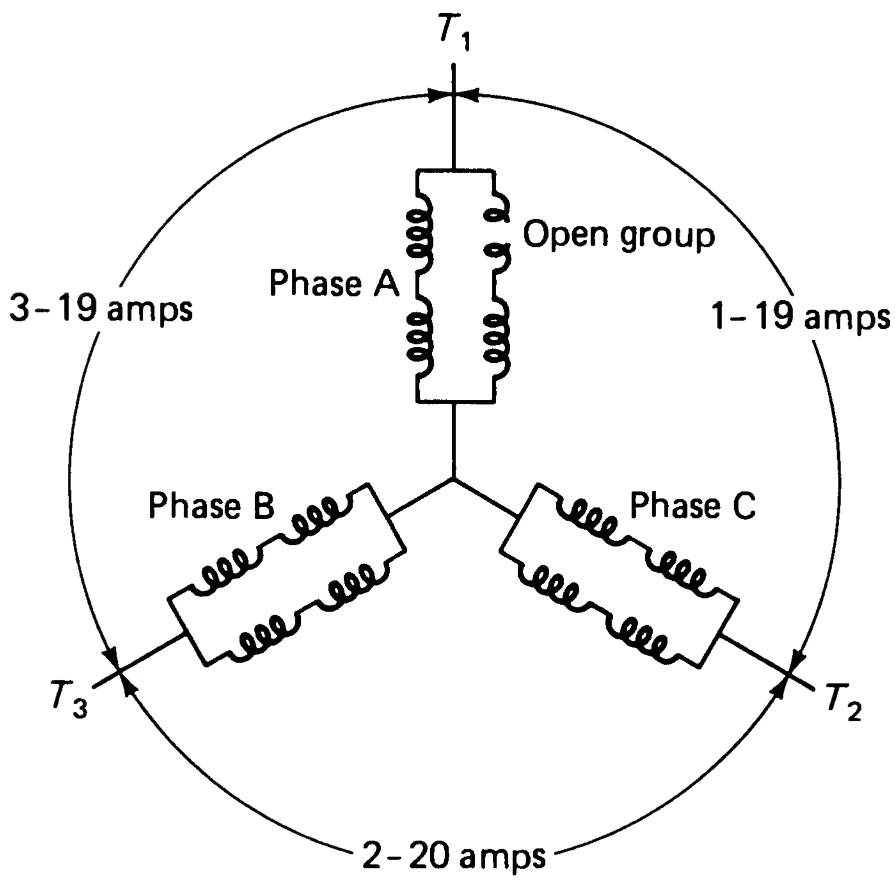


Fig. 3-166. Locating an open in a two-parallel wye motor using a test light.



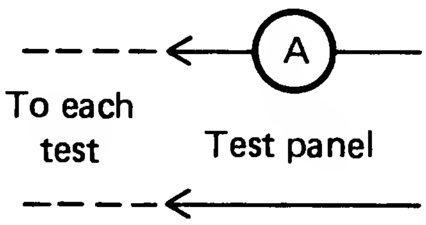
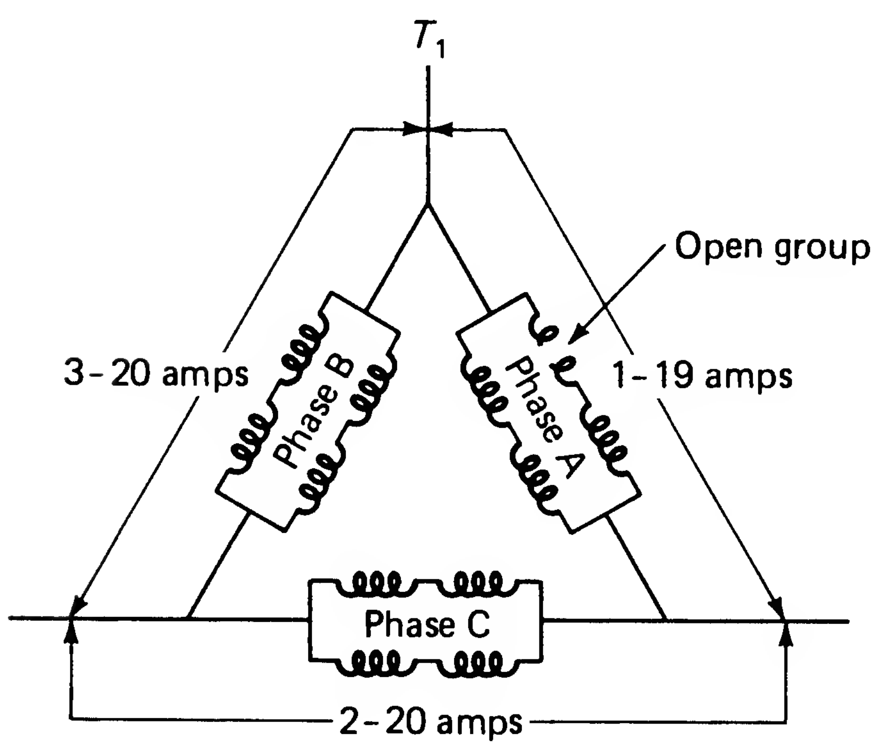


Fig. 3-167. Applying limited current to a winding to determine the open phase in a two-wye motor. The open phase will draw less current.



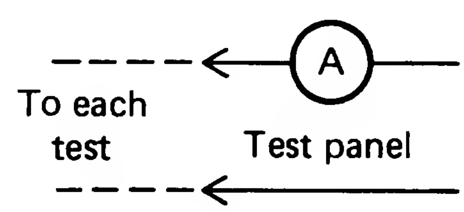


Fig. 3-168. Applying limited current to a winding to determine the open phase in a two-delta motor. The open phase will draw less current. The direction of current flow is explained in **Figs. 3-163a** and **b.**

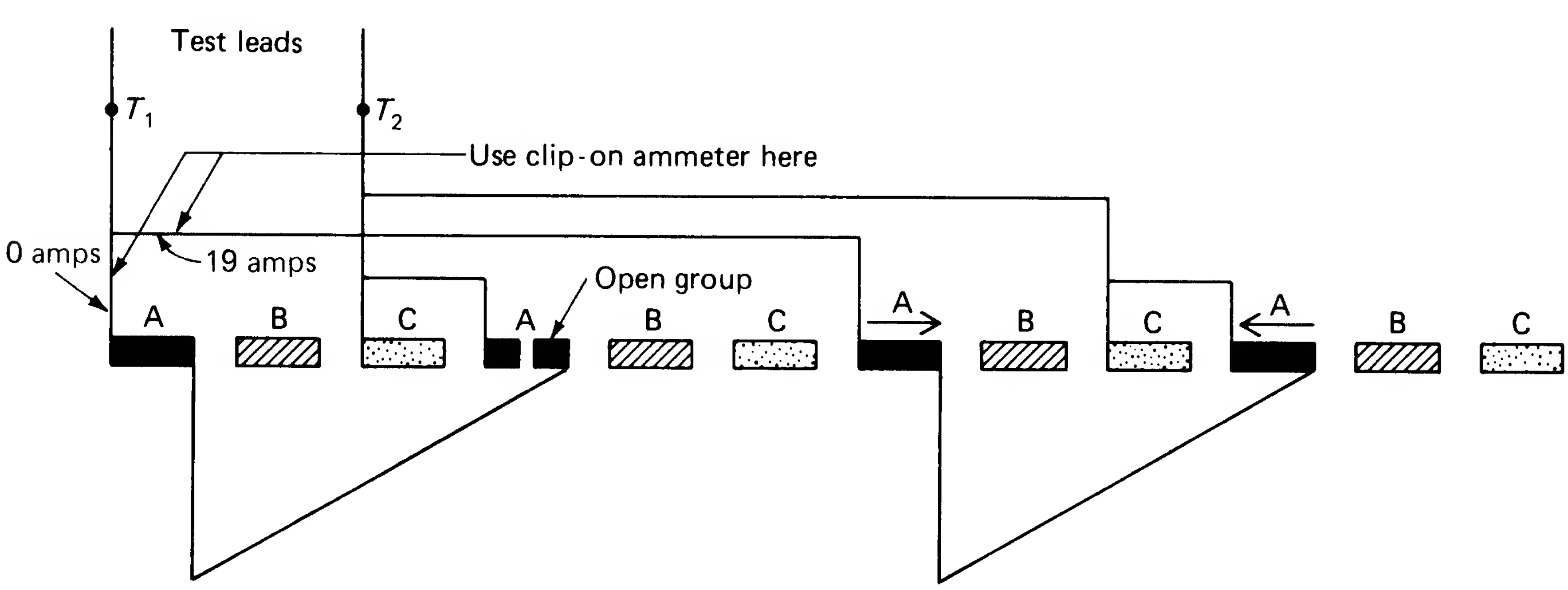


Fig. 3-169. Locating the open circuit of the *A* phase with a clip-on ammeter and limited current.

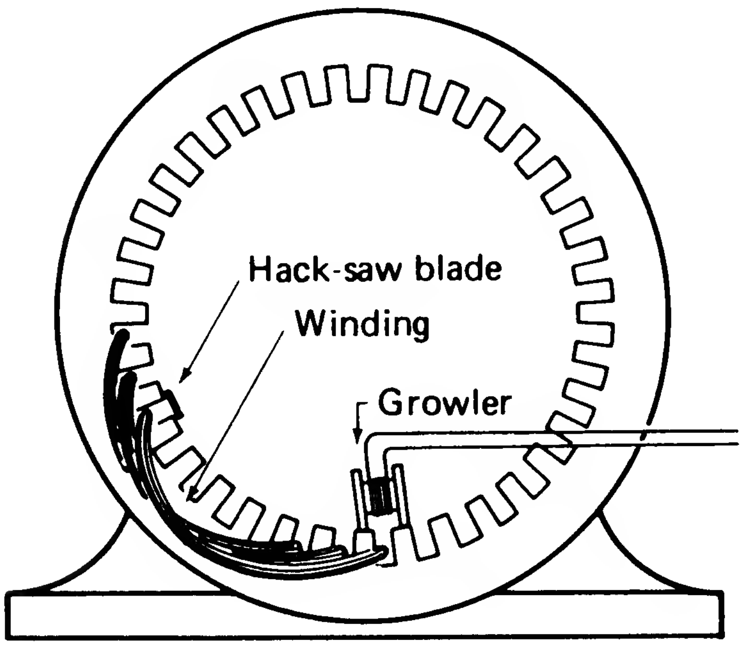


Fig. 3-170. The use of an internal growler to locate a shorted coil.

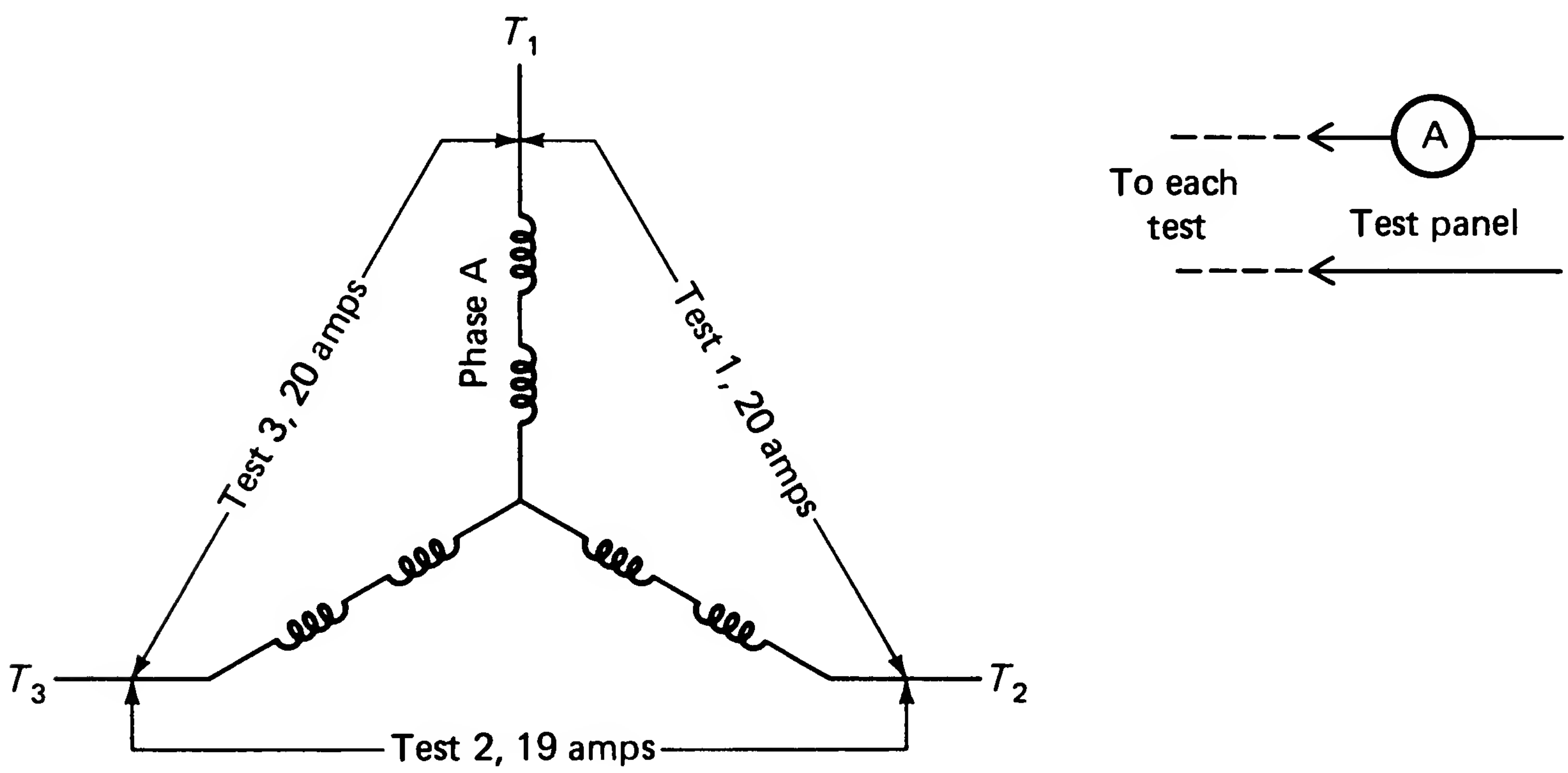


Fig. 3-171. Testing a one-wye winding using the balance method. The readings mean that the *A* phase may have a short.

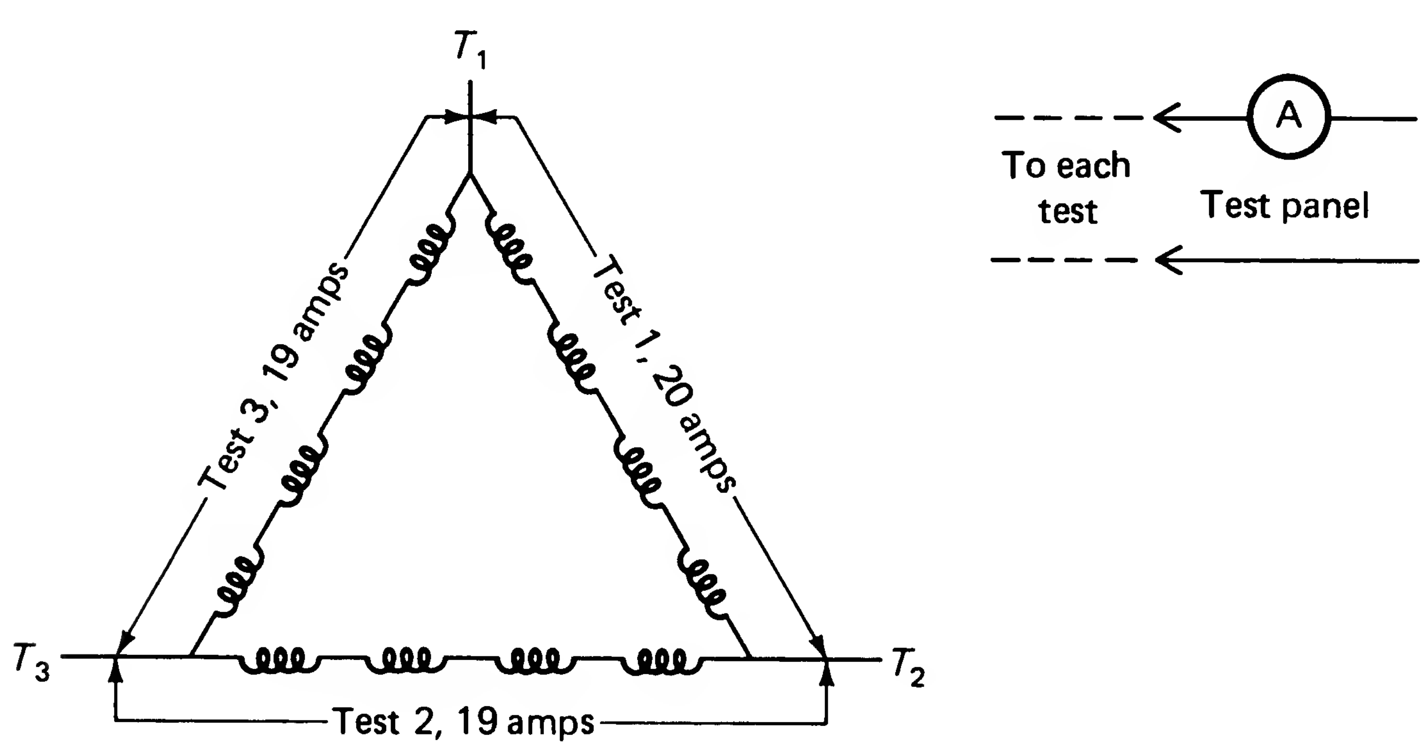


Fig. 3-172. Testing a one-delta winding using the balance method. The readings mean that the *A* phase may have a short.

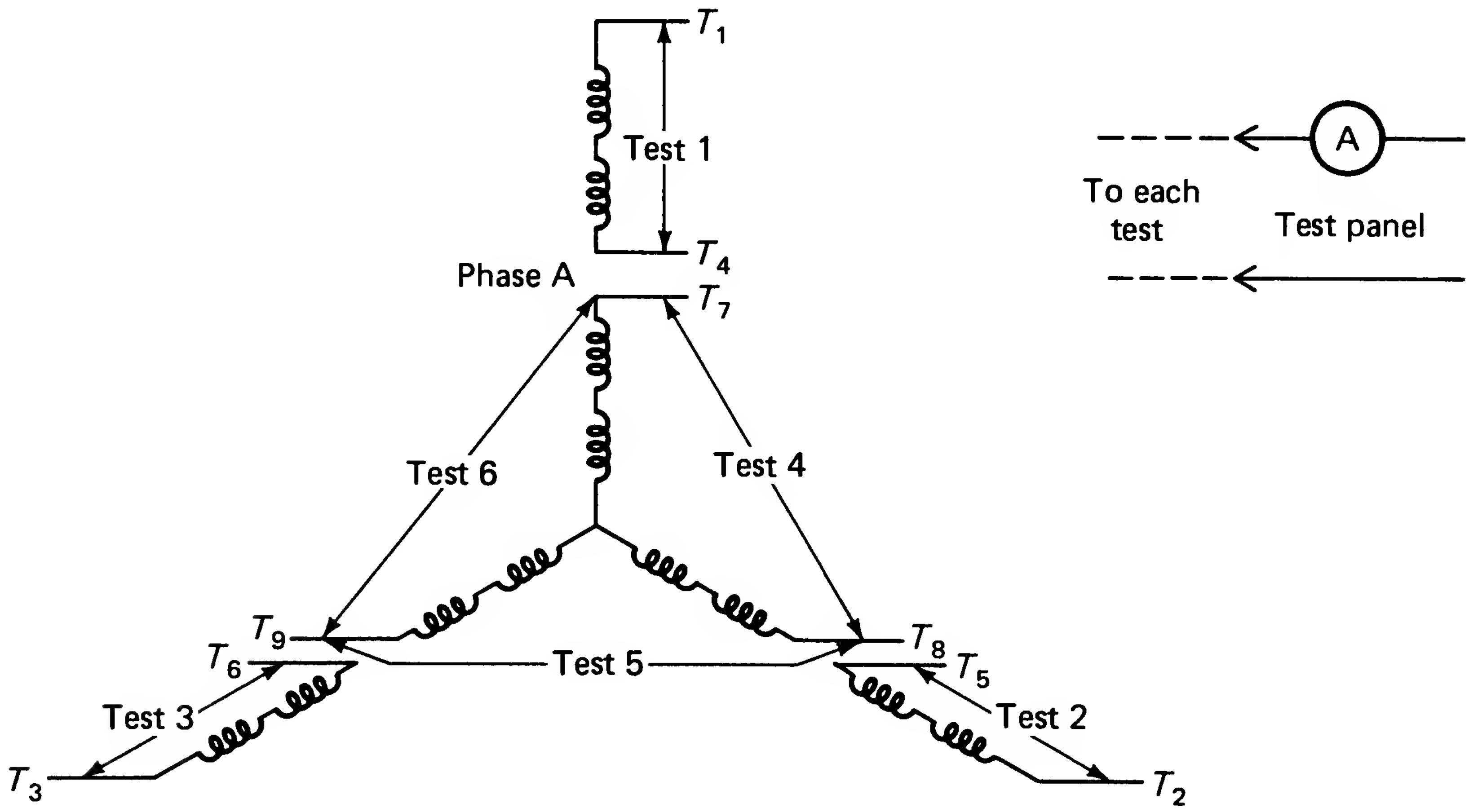


Fig. 3–173a. Using the balance test on a one- and two-wye winding to locate shorts. Tests 1, 2, and 3 should have the same amp reading. Tests 4, 5, and 6 will read lower but should all be the same. If tests 4 and 6 are higher than test 5, the short will be in the *A* phase.

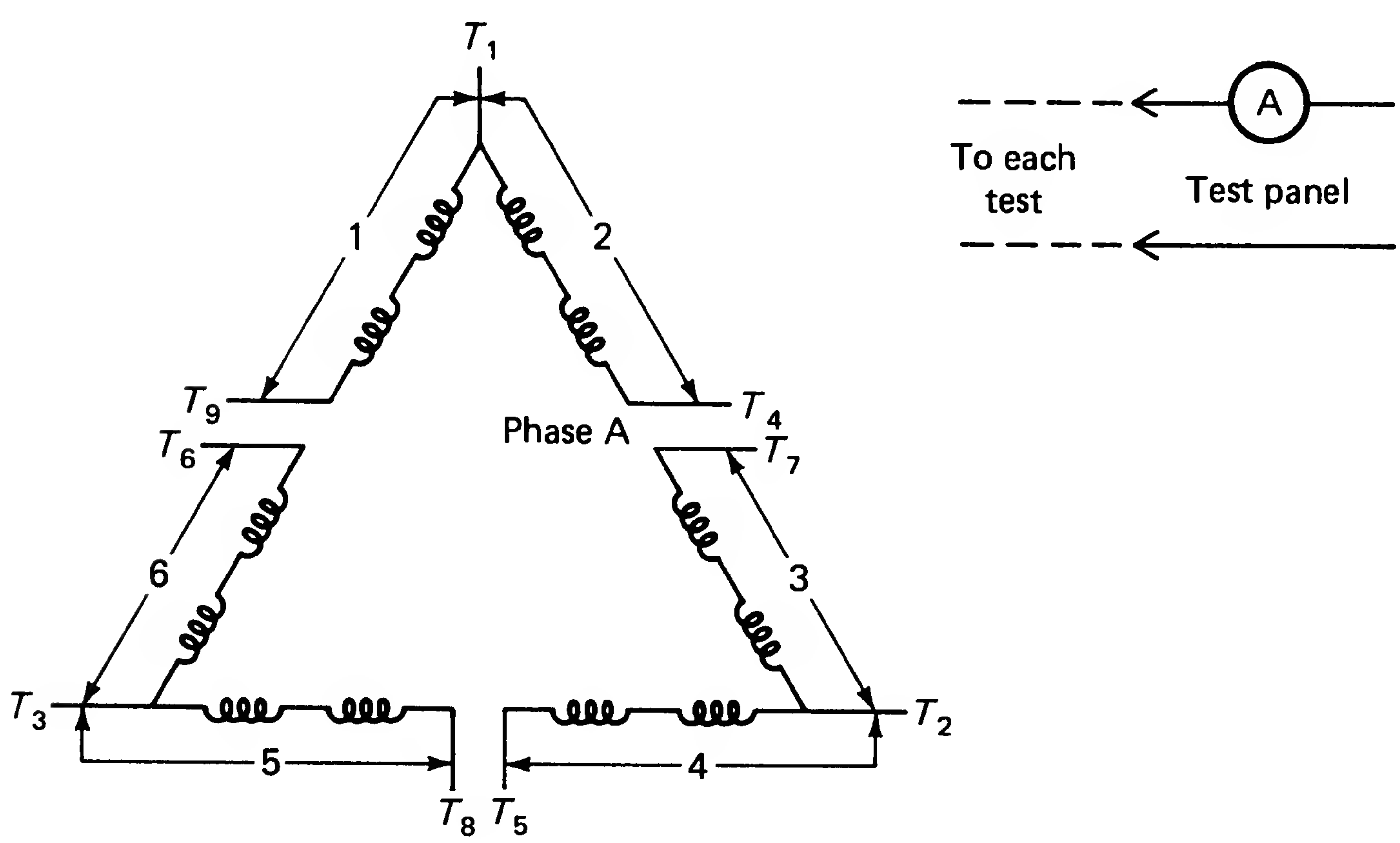


Fig. 3–173b. Using the balance test on a one- and two-delta winding to locate shorts. All tests should have the same amp reading. A higher reading on any test may mean a short.

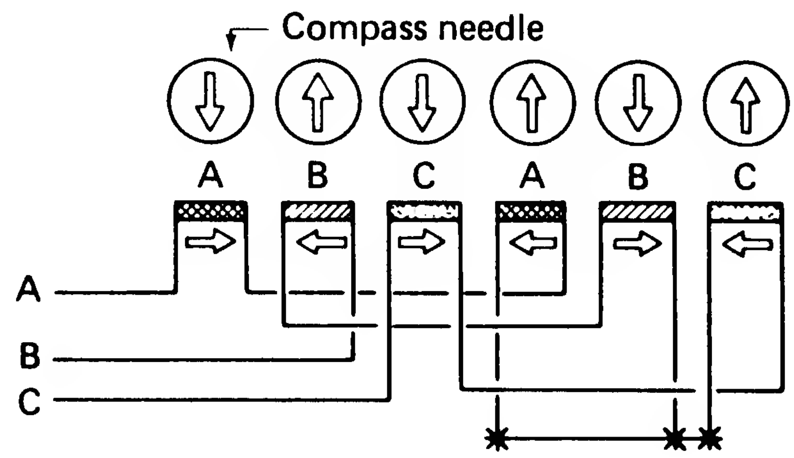


Fig. 3–174. The correct method of connecting a three-phase, two-pole star (wye) motor is indicated by the compass needle.

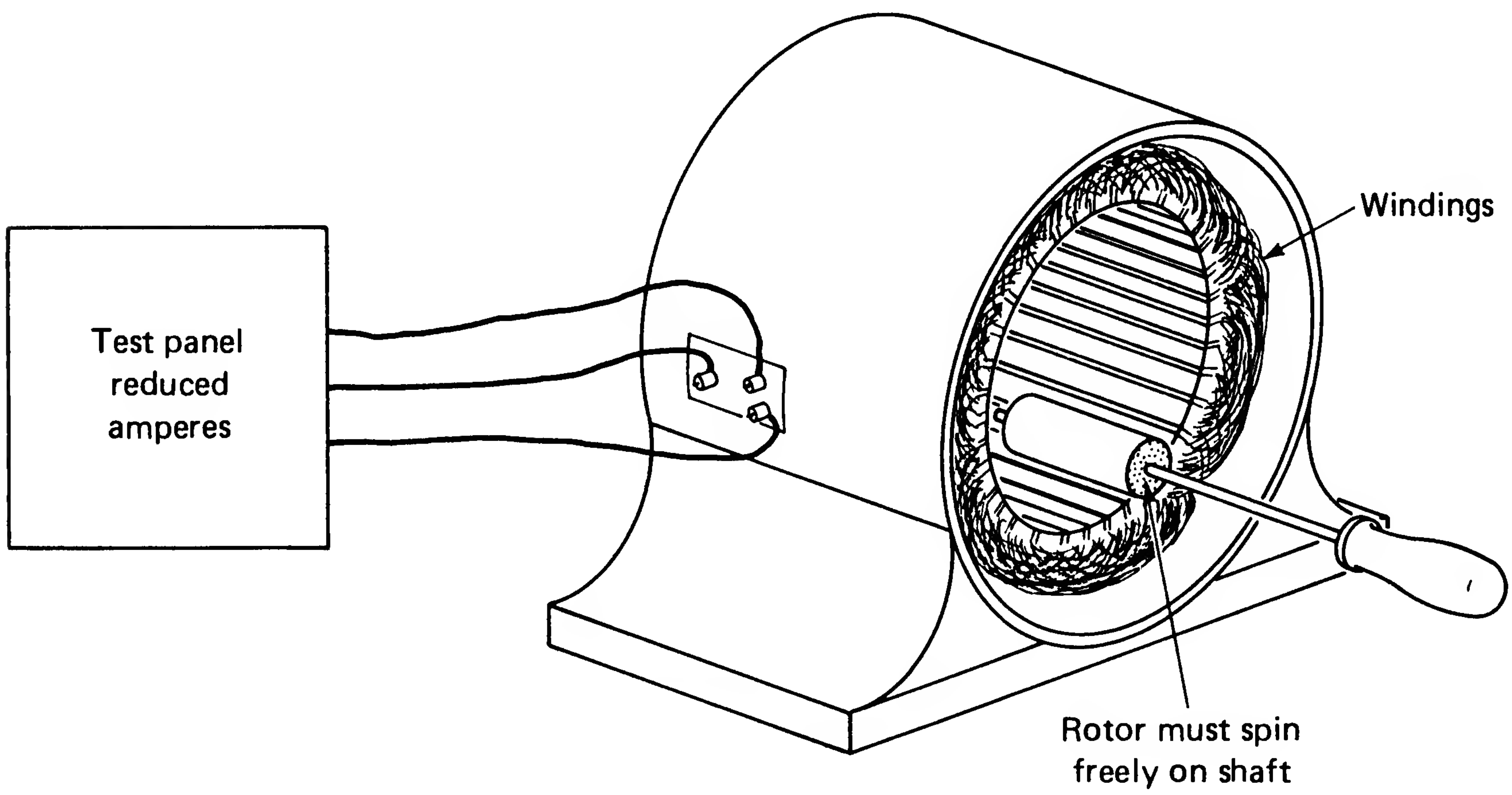


Fig. 3–175. A test rotor used to find reversed coils or coil groups in stators.

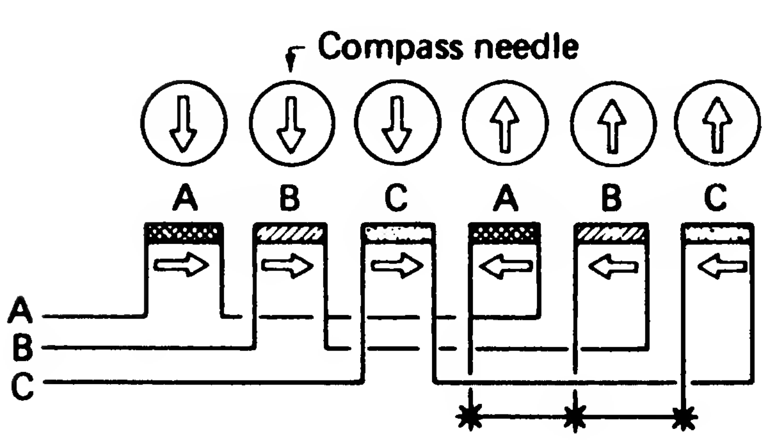


Fig. 3–176. An incorrect connection of phase *B*. Reverse this phase.

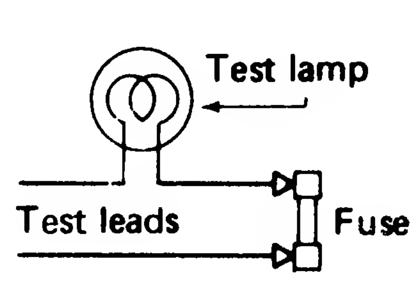


Fig. 3–177. Testing a fuse with a test lamp.

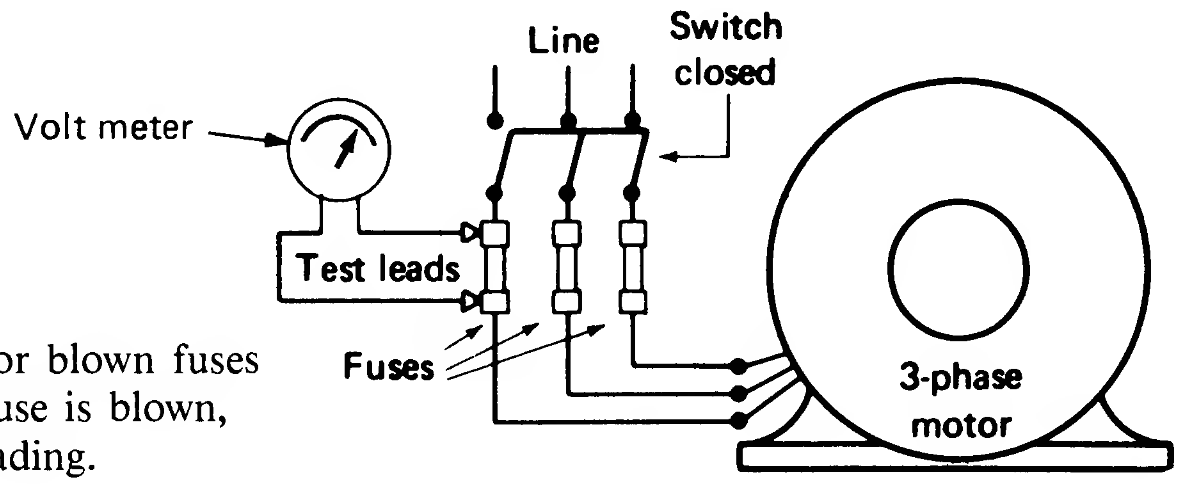


Fig. 3–178. Testing for blown fuses with a voltmeter. If the fuse is blown, there will be a voltage reading.

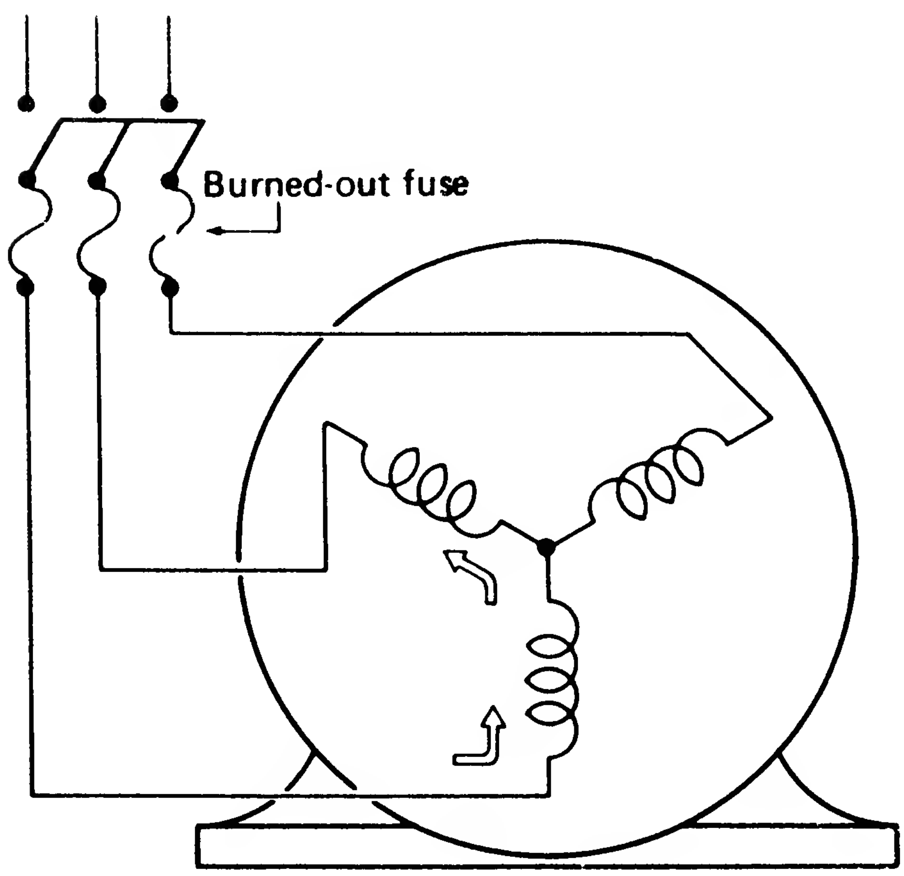


Fig. 3–179. A star-connected motor with burned-out fuse in one phase. Current through the other two phases will overload the coils and burn them out.

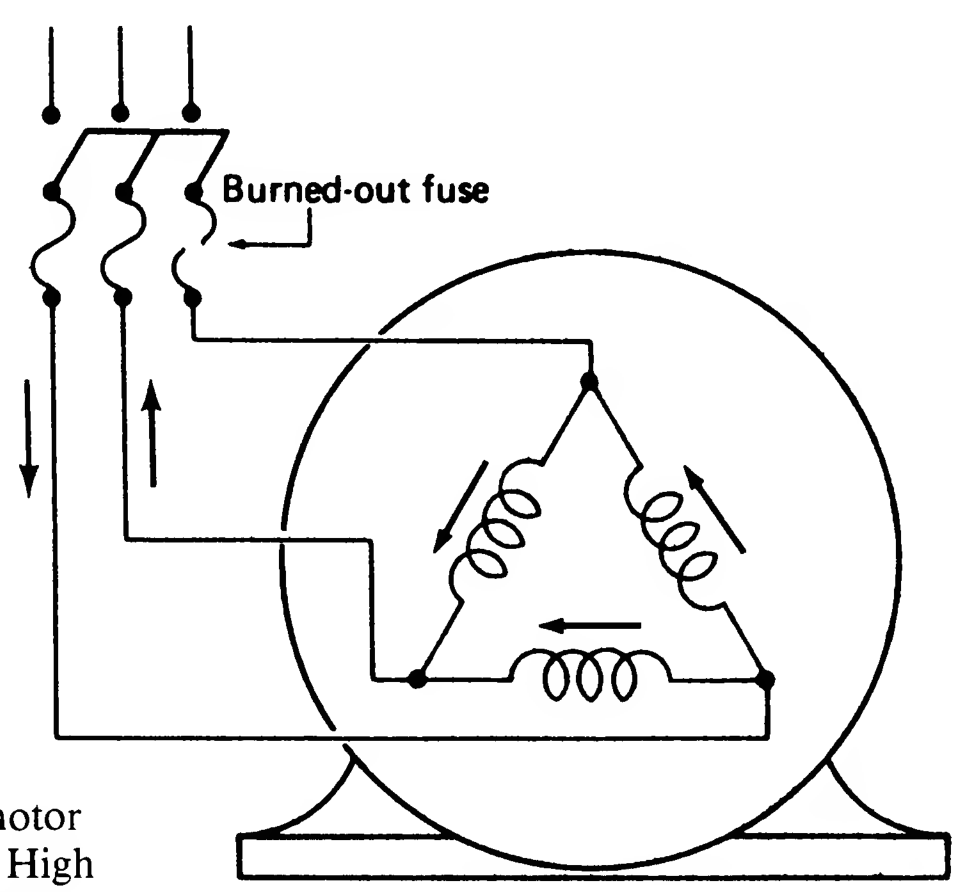


Fig. 3–180. A delta-connected motor with burned-out fuse in one phase. High current will flow in one of the phases.

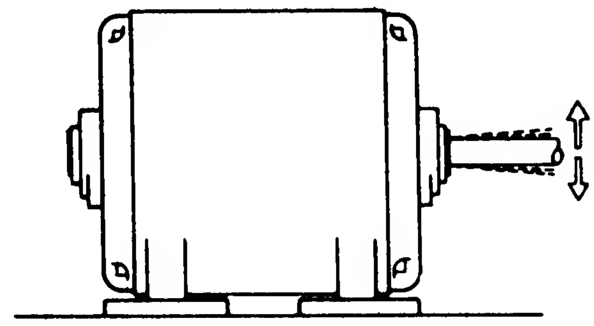


Fig. 3-181. Lift the shaft up and down. Movement indicates worn bearing of shaft.

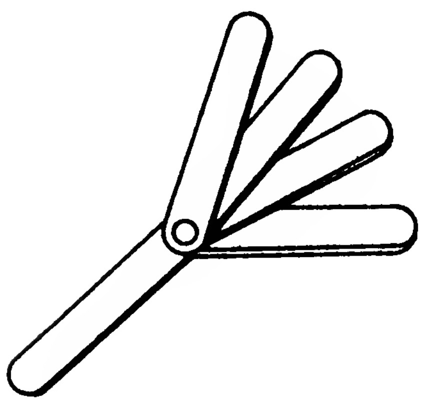


Fig. 3-182. A feeler gauge, which has thin metal strips of different thickness.

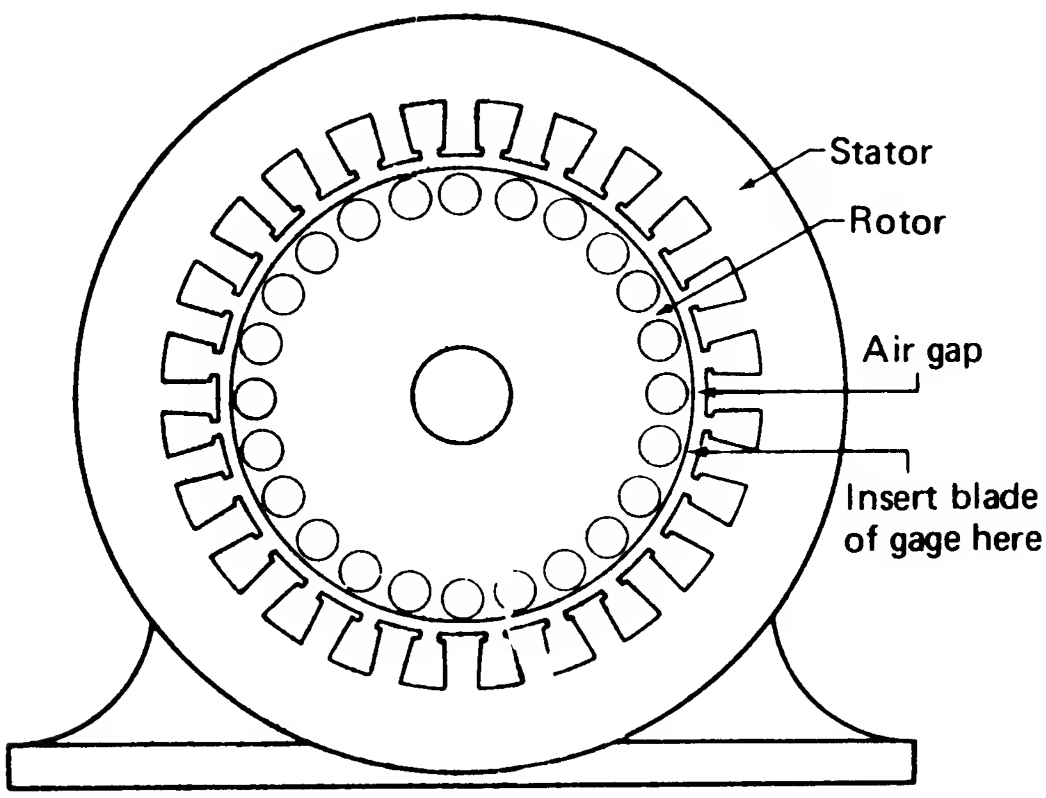


Fig. 3-183. The air gap should be the same around the entire motor. This is checked with a feeler gauge.

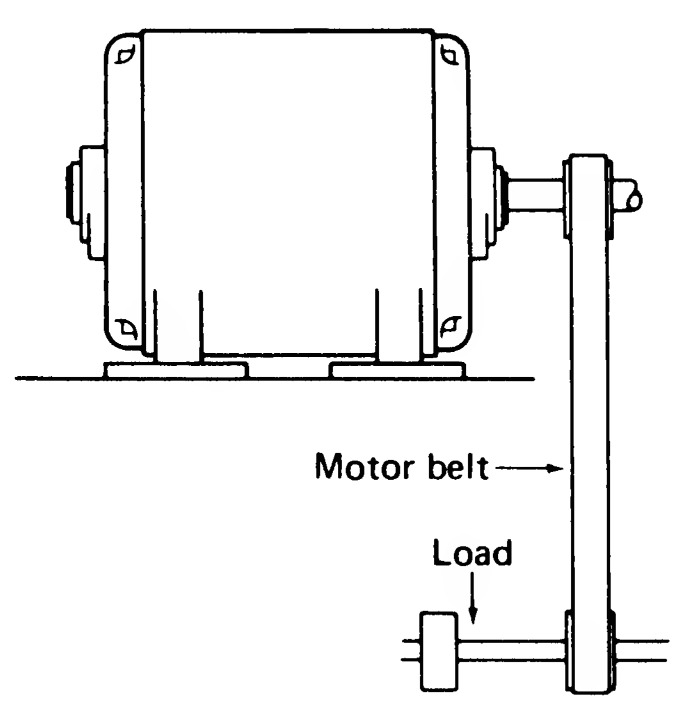


Fig. 3-184. Disconnect belt and try to move load in order to see if load is free to turn.

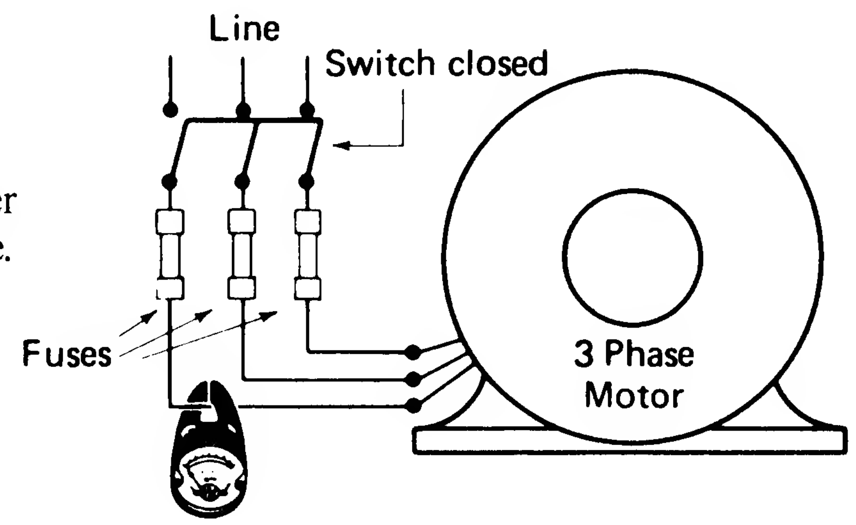


Fig. 3-185. Snap around ammeter used to determine current in each line.

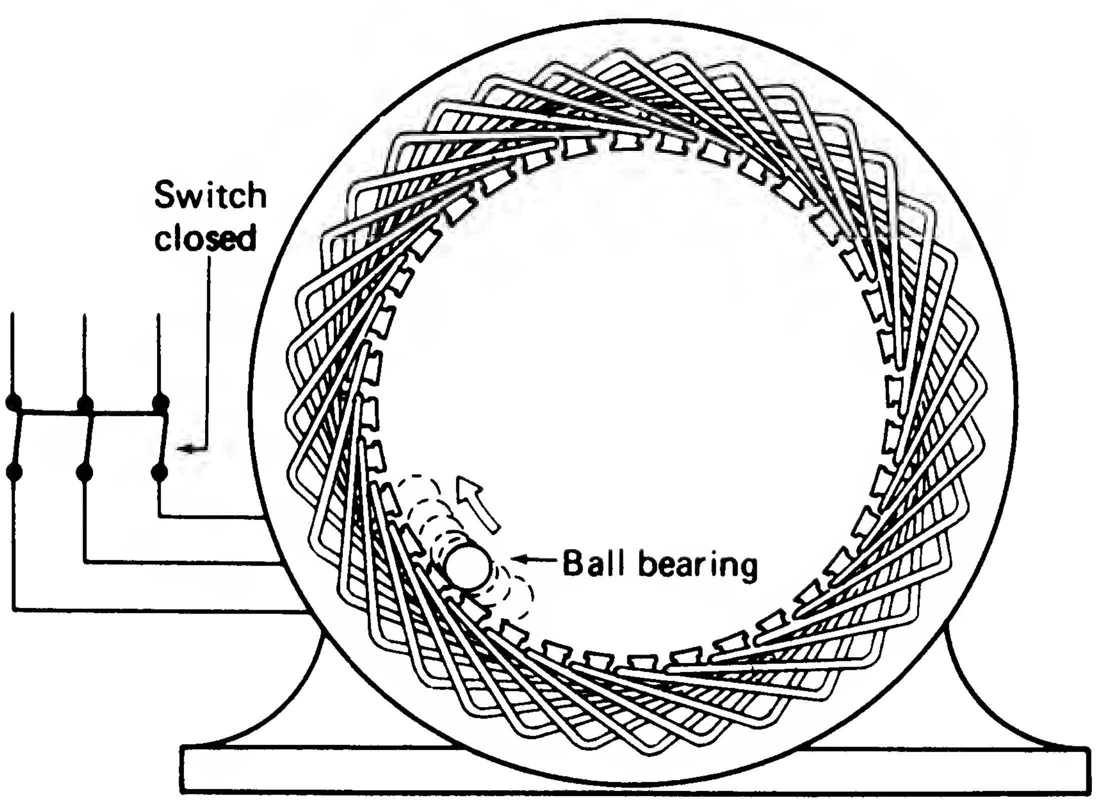


Fig. 3-186. The ball bearing should rotate around the core of the stator if internal connections are correct.

CHAPTER 4

Alternating-current Motor Control

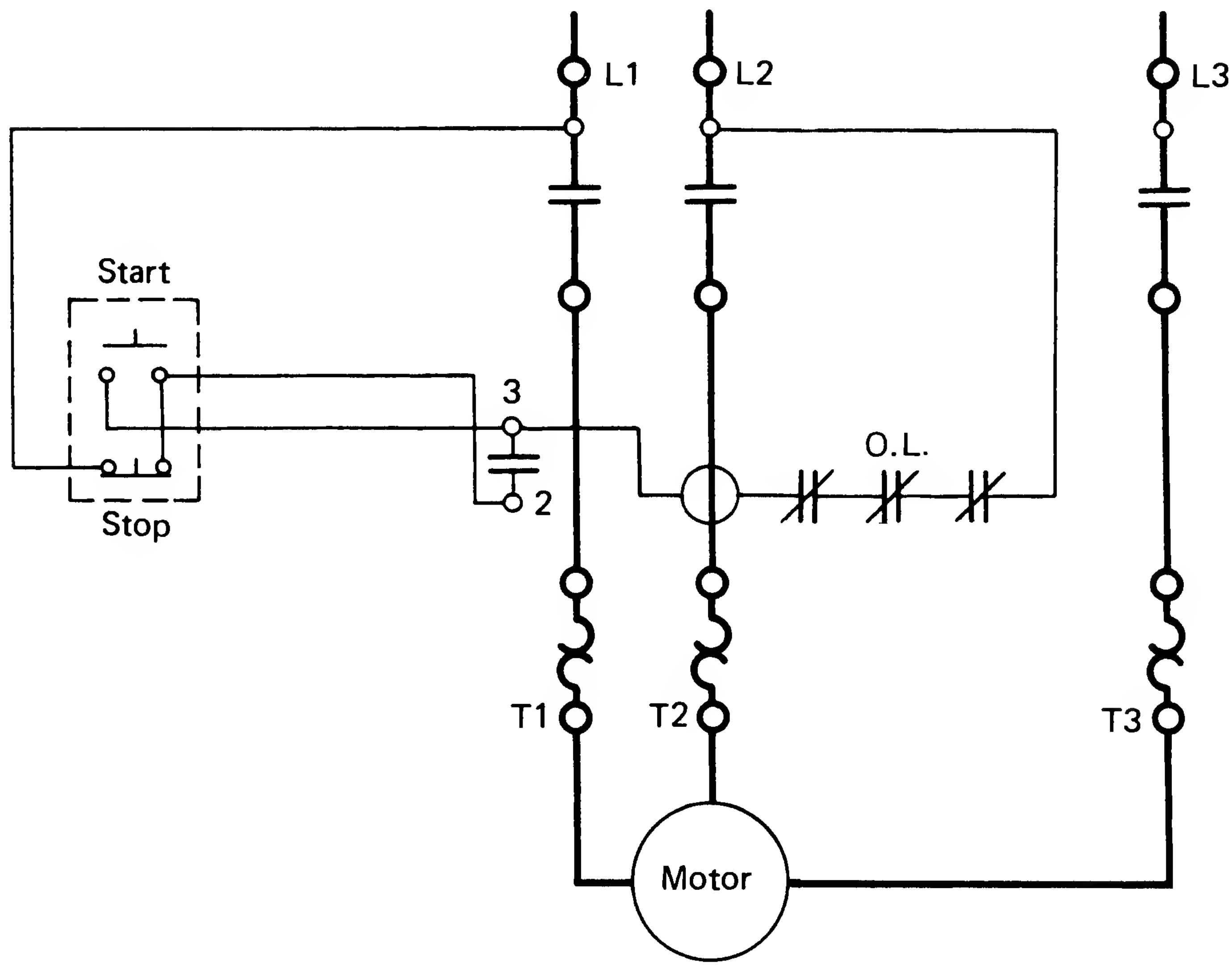


Fig. 4-1. A wiring diagram of a standard START-STOP pushbutton station. (*Allen-Bradley Co.*)

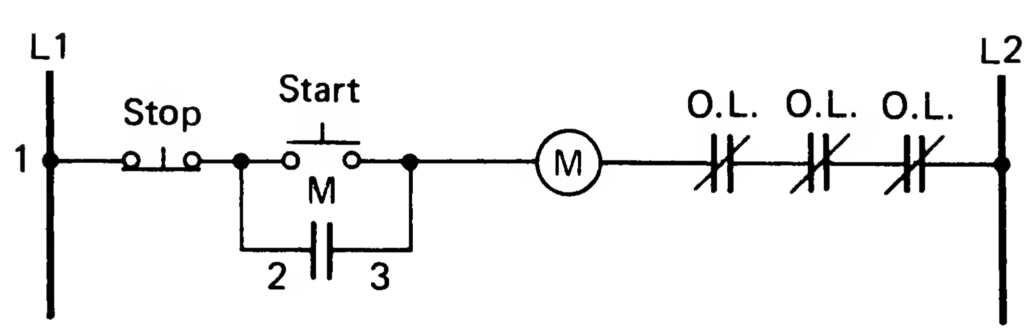


Fig. 4-2. A line diagram of a START-STOP pushbutton station. (*Allen-Bradley Co.*)

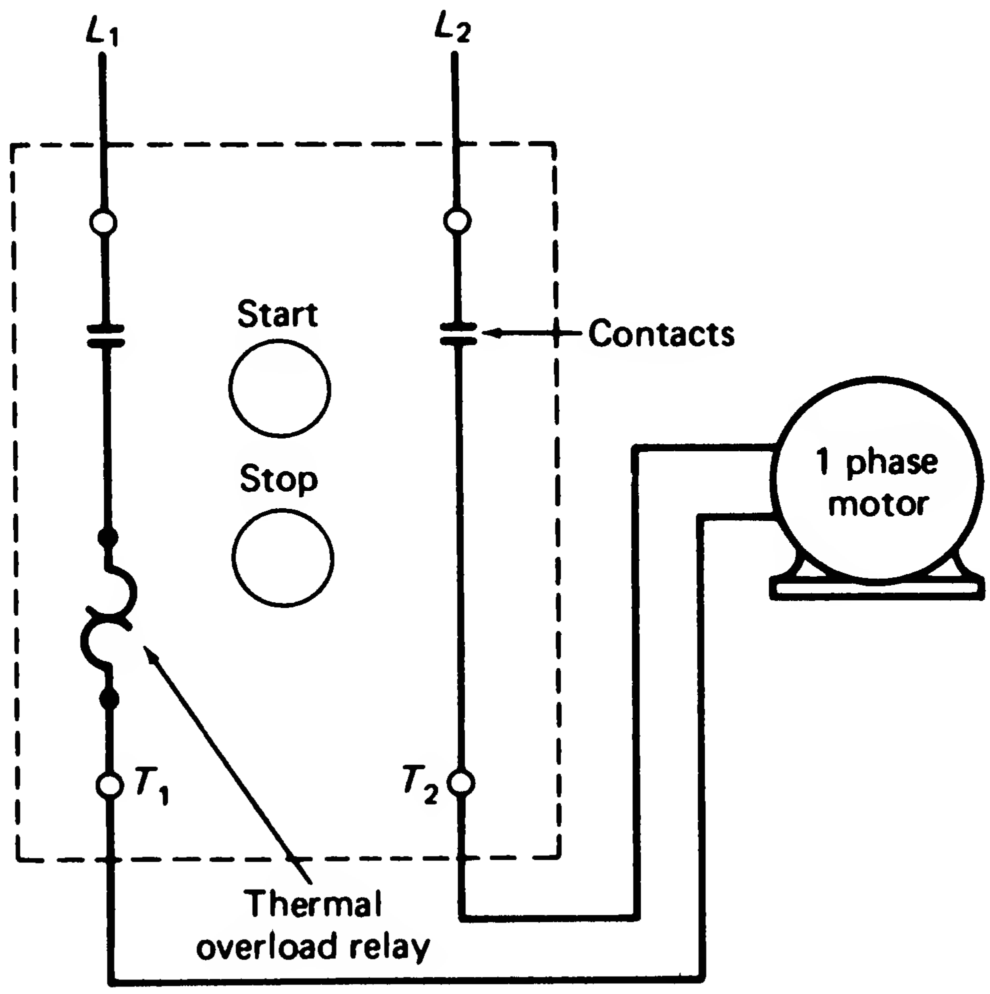


Fig. 4-3. A pushbutton switch starter connected to a single-phase motor.

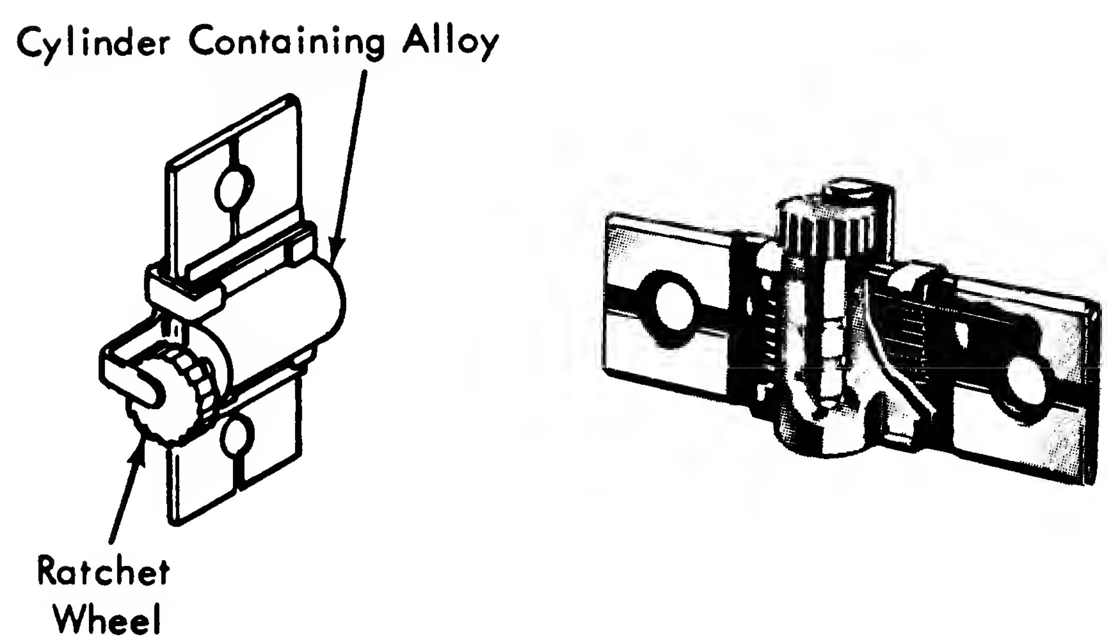


Fig. 4-4. A thermal relay of the melting-alloy type.

Figures 4-3; 4-4

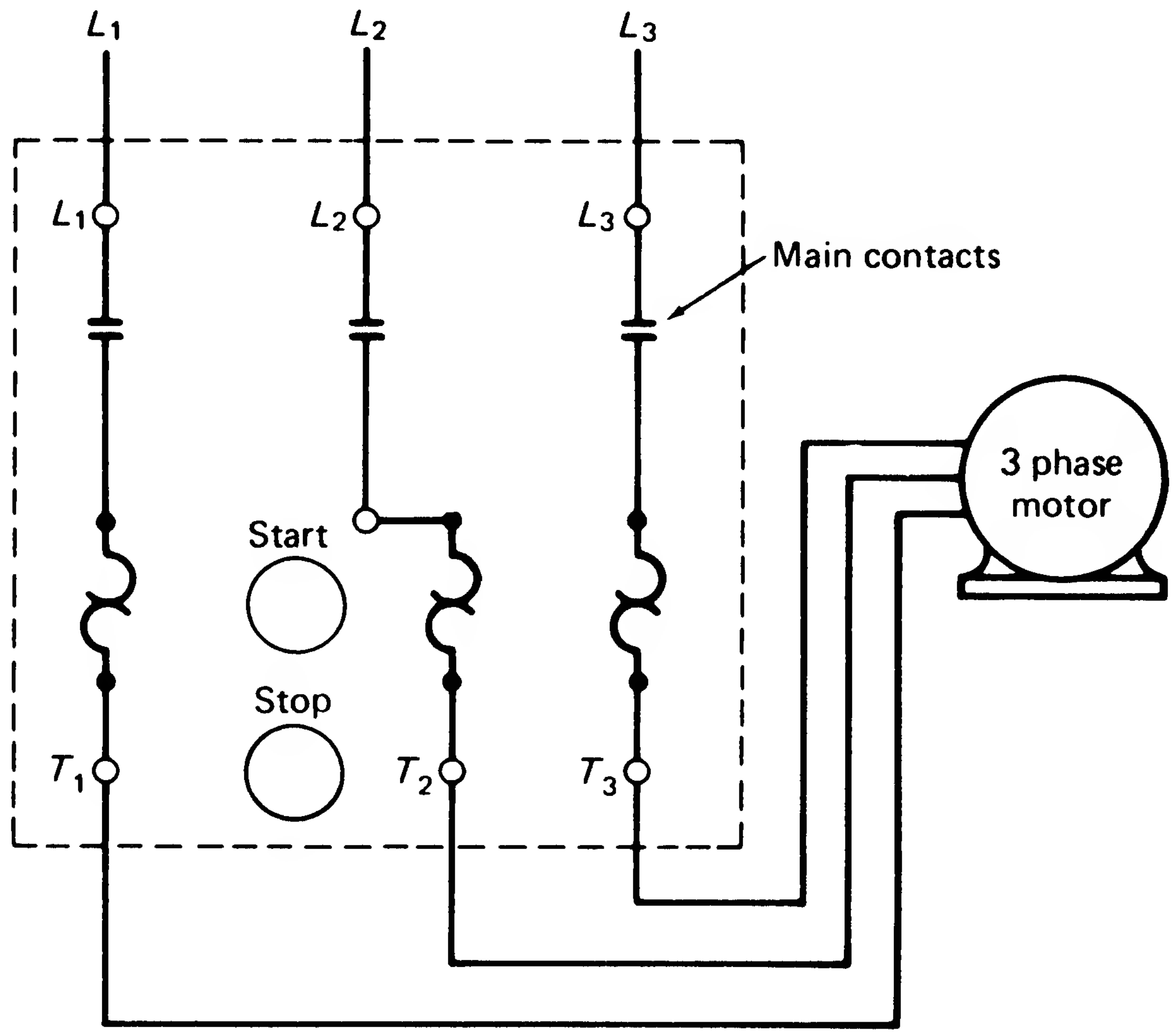


Fig. 4-5. A pushbutton switch starter connected to a three-phase motor.

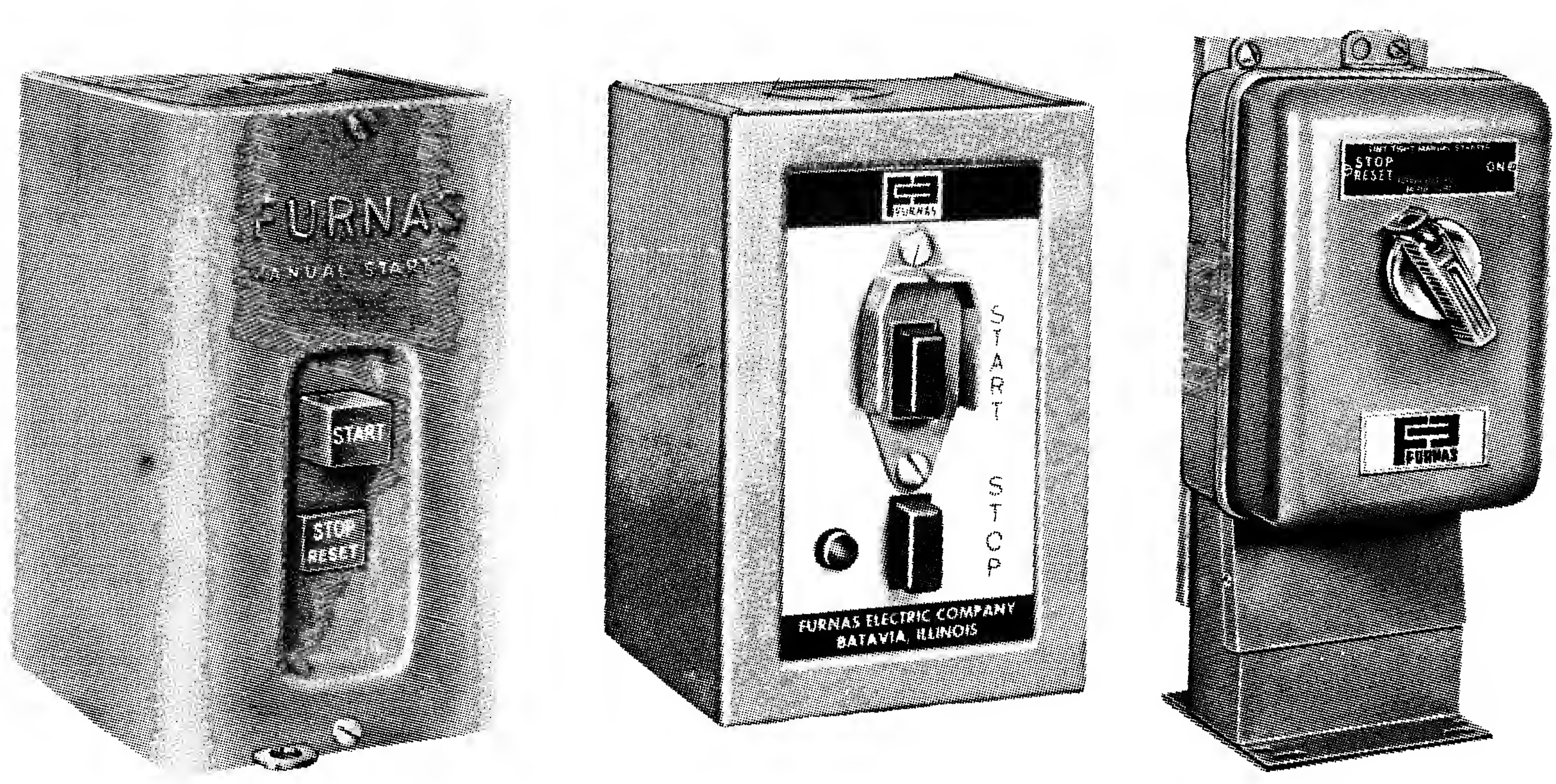


Fig. 4-6. Types of manual starters. (*Furnas Electric Co.*)

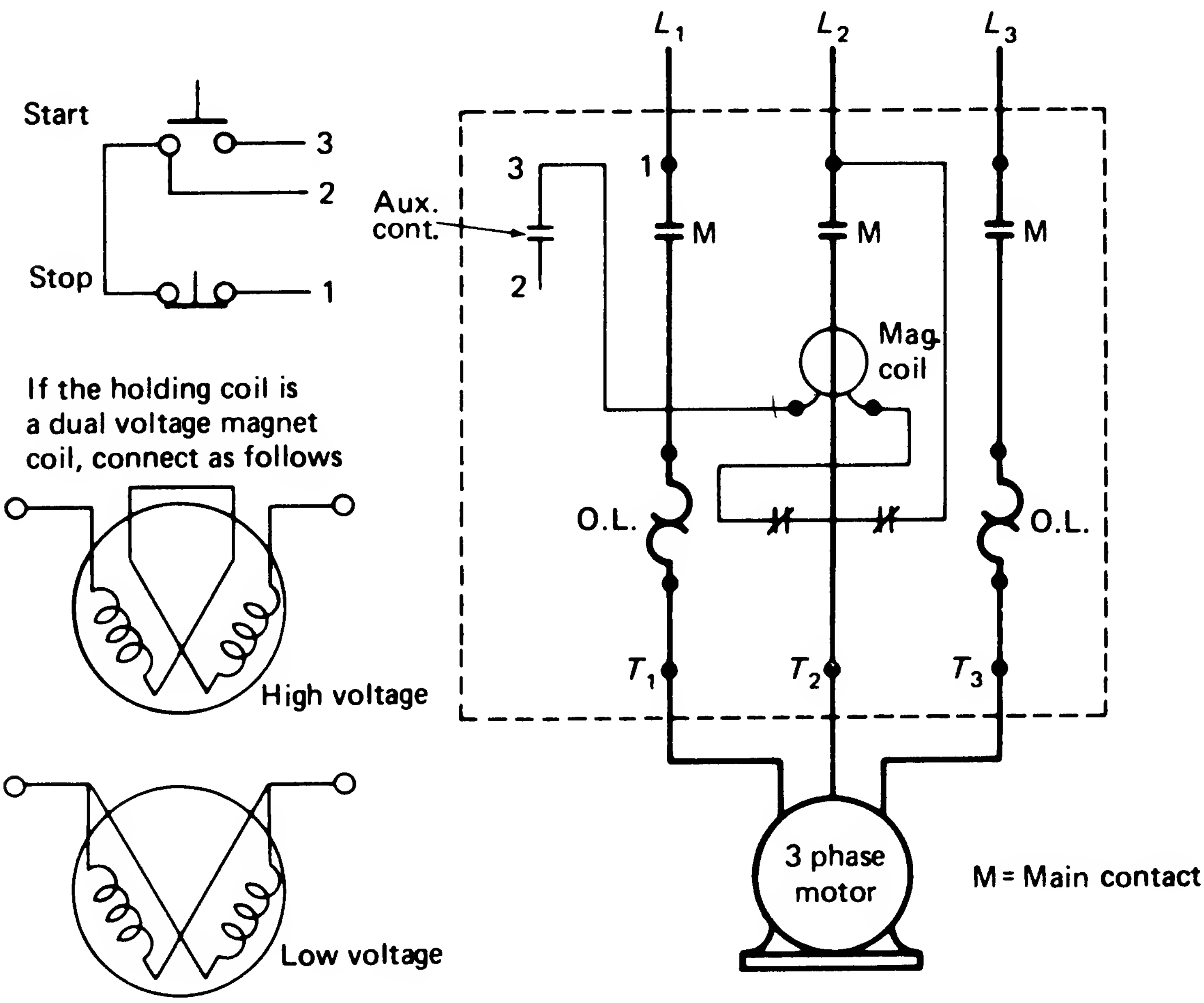


Fig. 4-7. A magnetic across-the-line starter connected to a three-phase motor. This is an older starter with two overload relays.

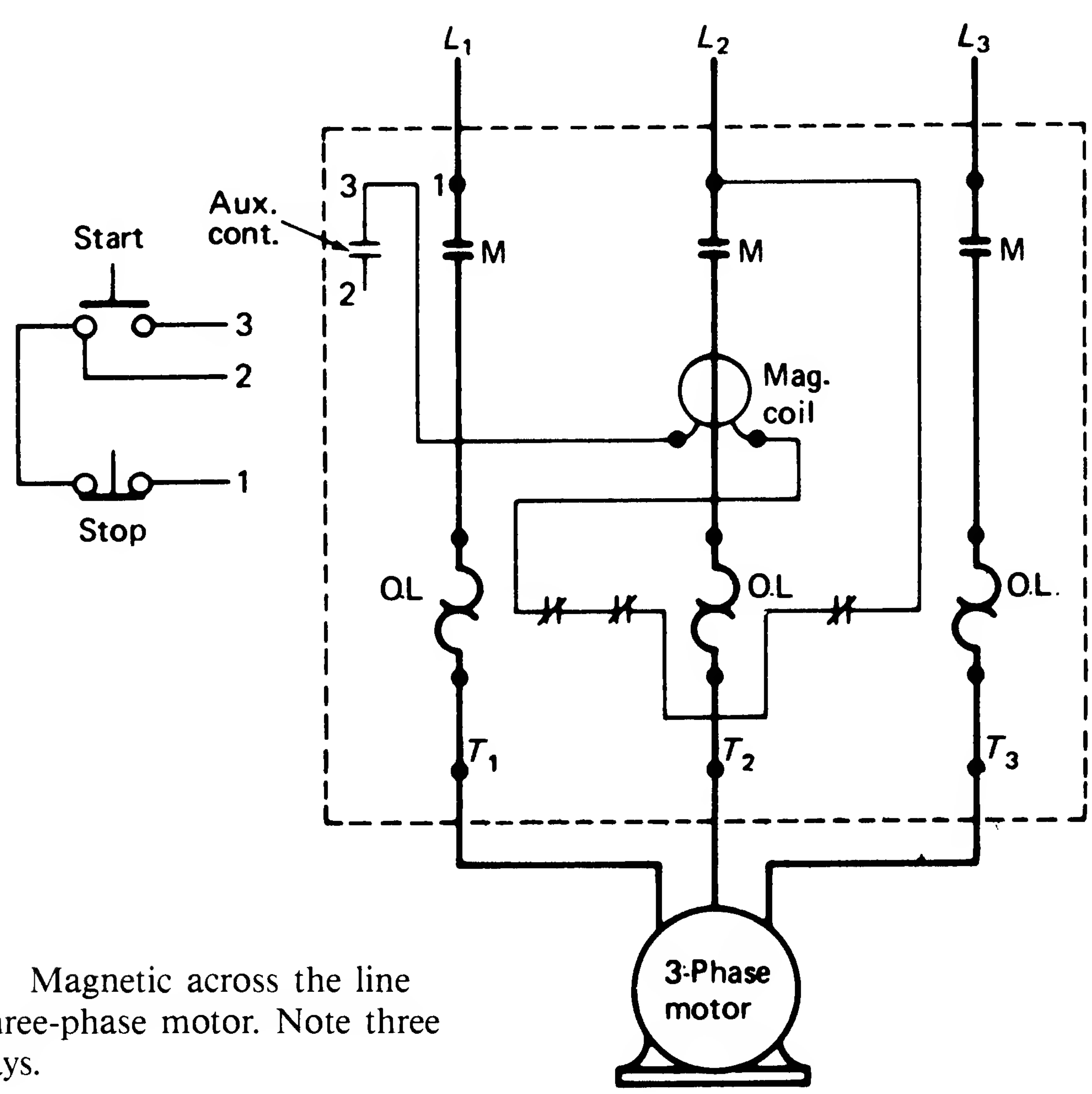


Fig. 4-8. Magnetic across the line starter for three-phase motor. Note three overload relays.

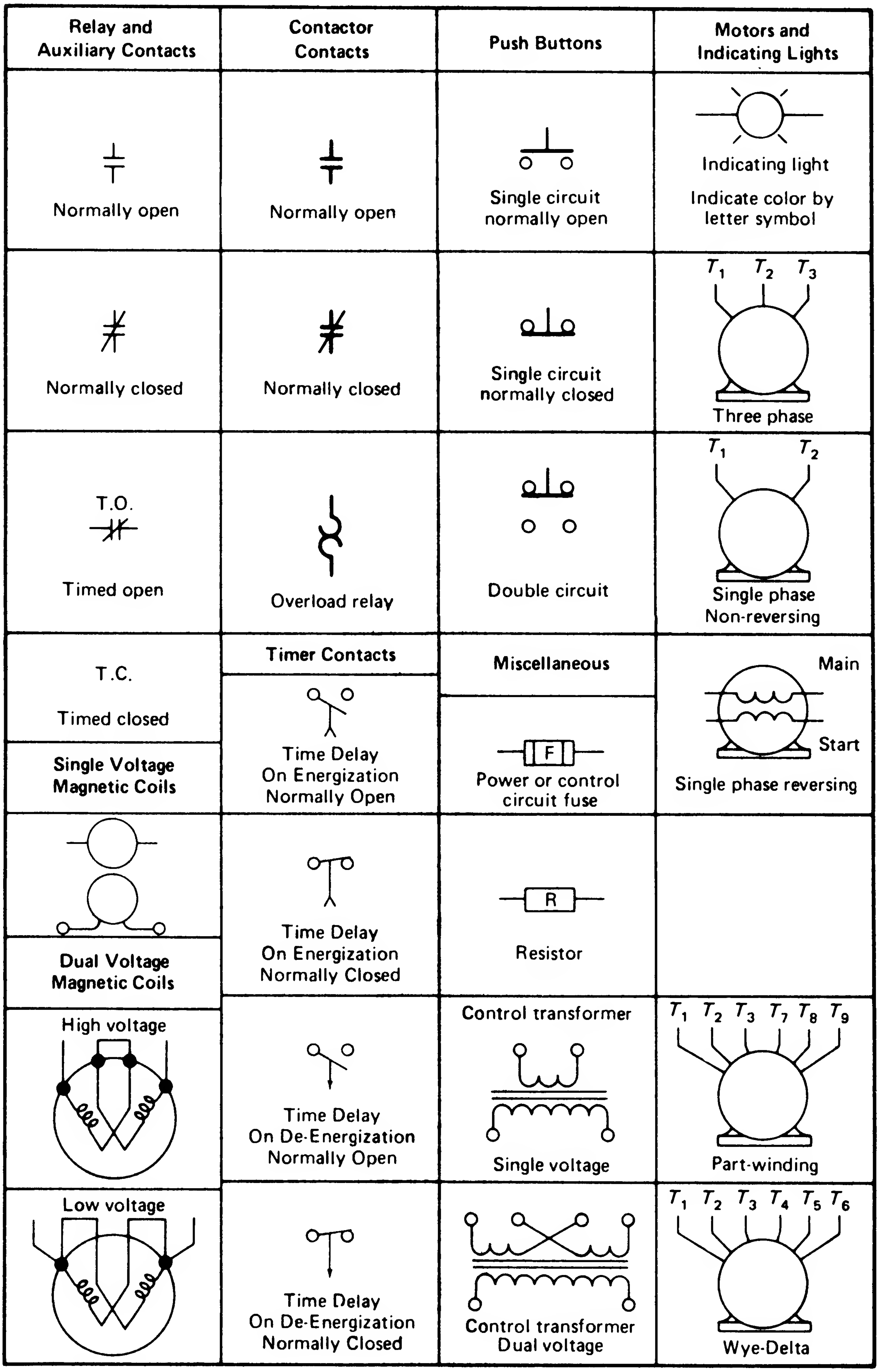


Fig. 4–9. Wiring diagram symbols.

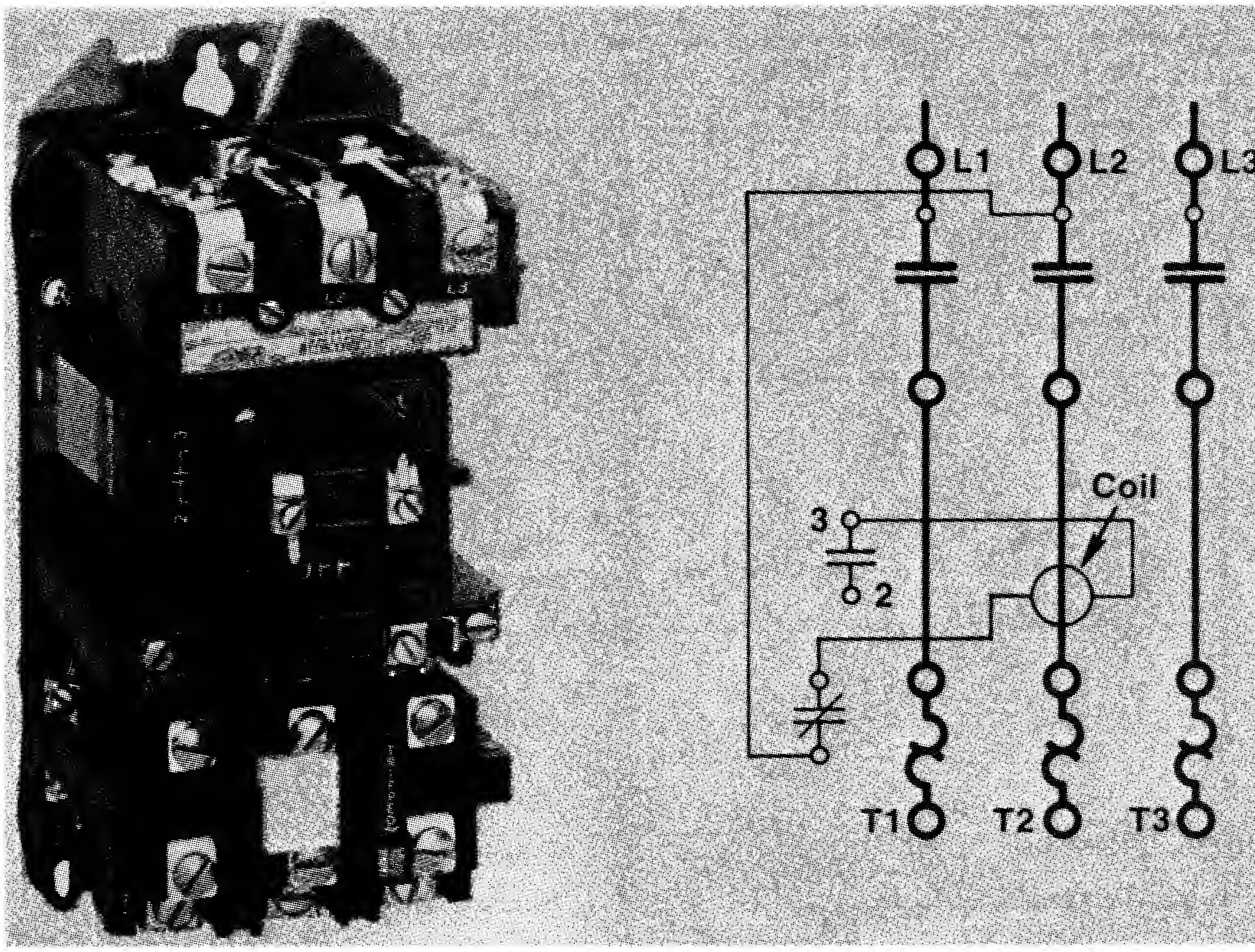


Fig. 4-10. Magnetic starter for a three-phase motor. (*Allen-Bradley Co.*)

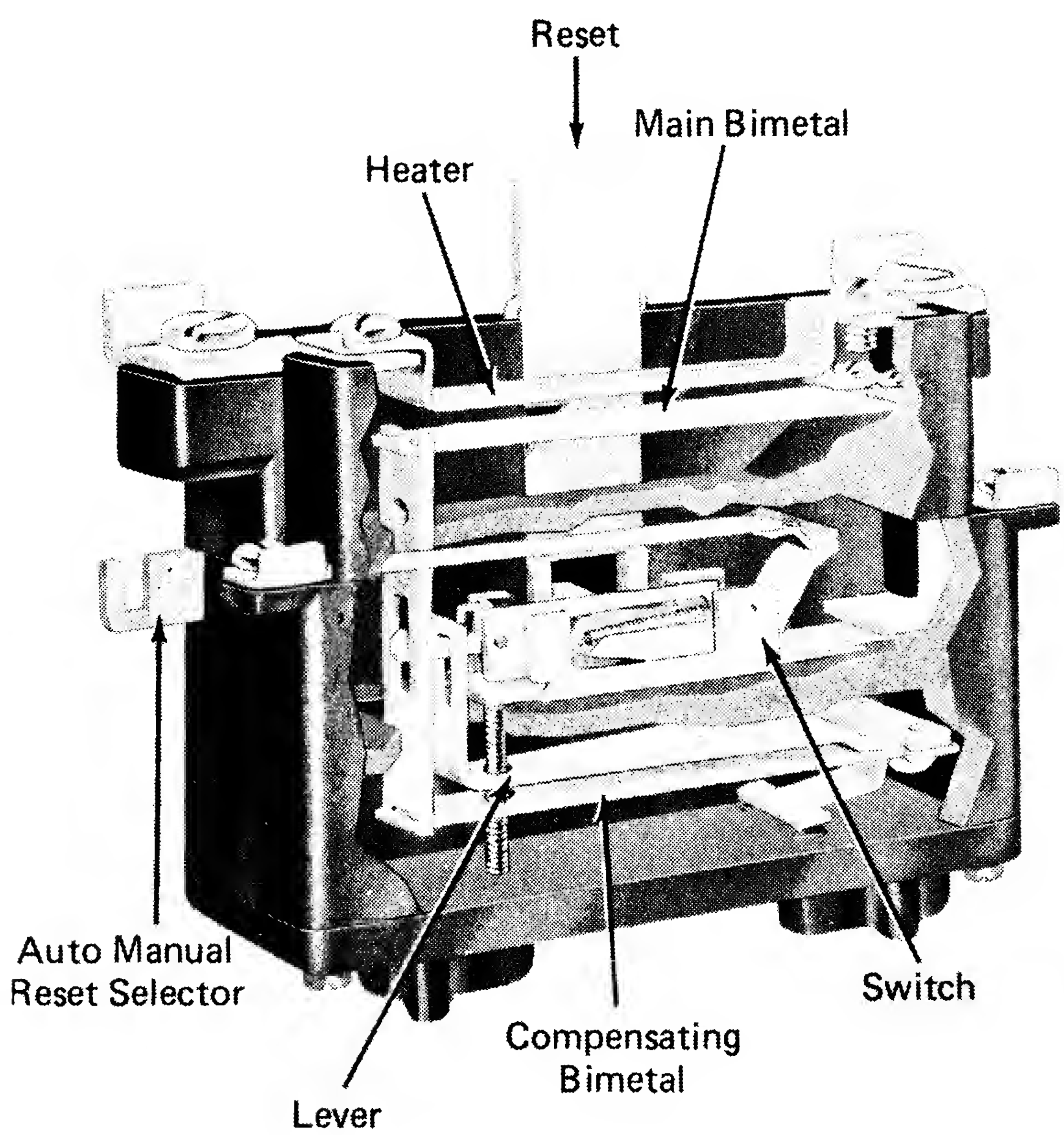


Fig. 4-11a. Bimetallic overload relay. (*Furnas Electric Co.*)

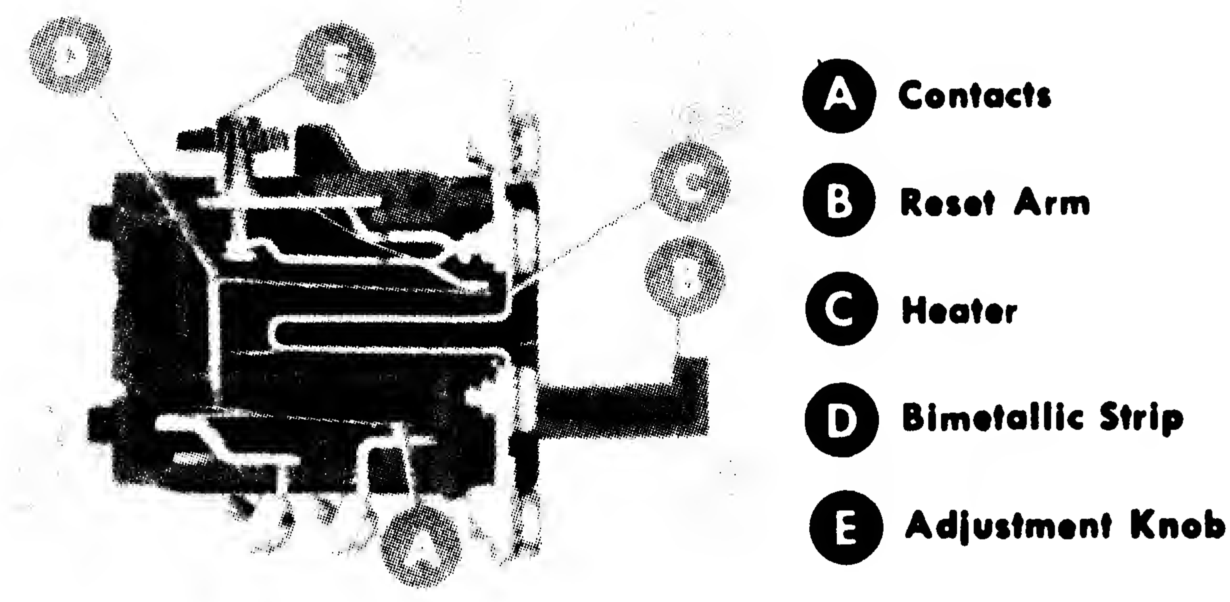


Fig. 4-11b. Bimetallic overload relay. (*General Electric Co.*)

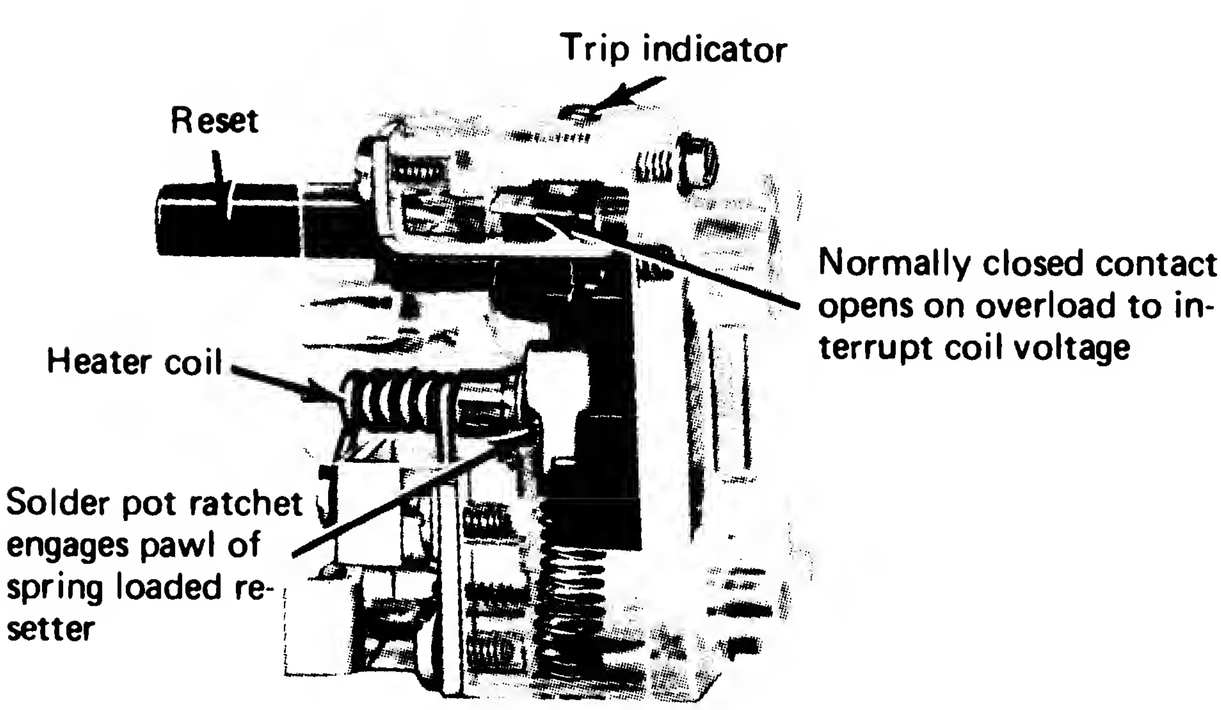
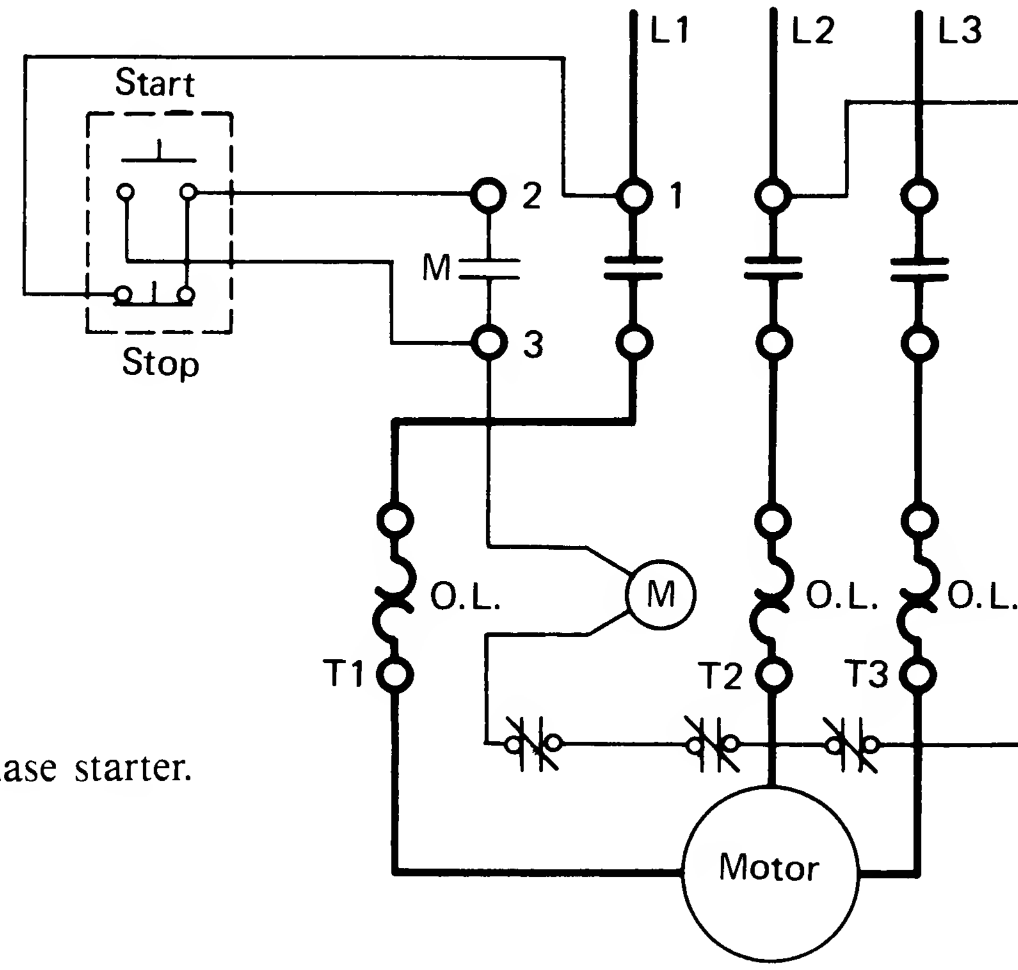


Fig. 4-12. Melting alloy overload relay. (*Furnas Electric Co.*)



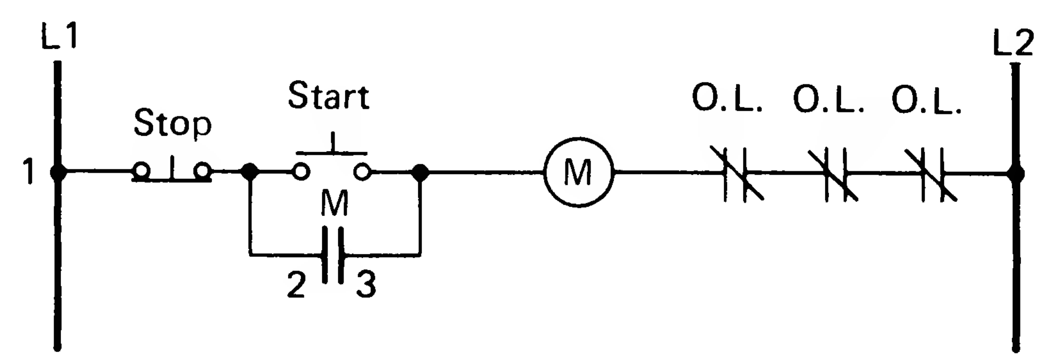


Fig. 4-13a. A three-phase starter. (*Allen-Bradley Co.*)

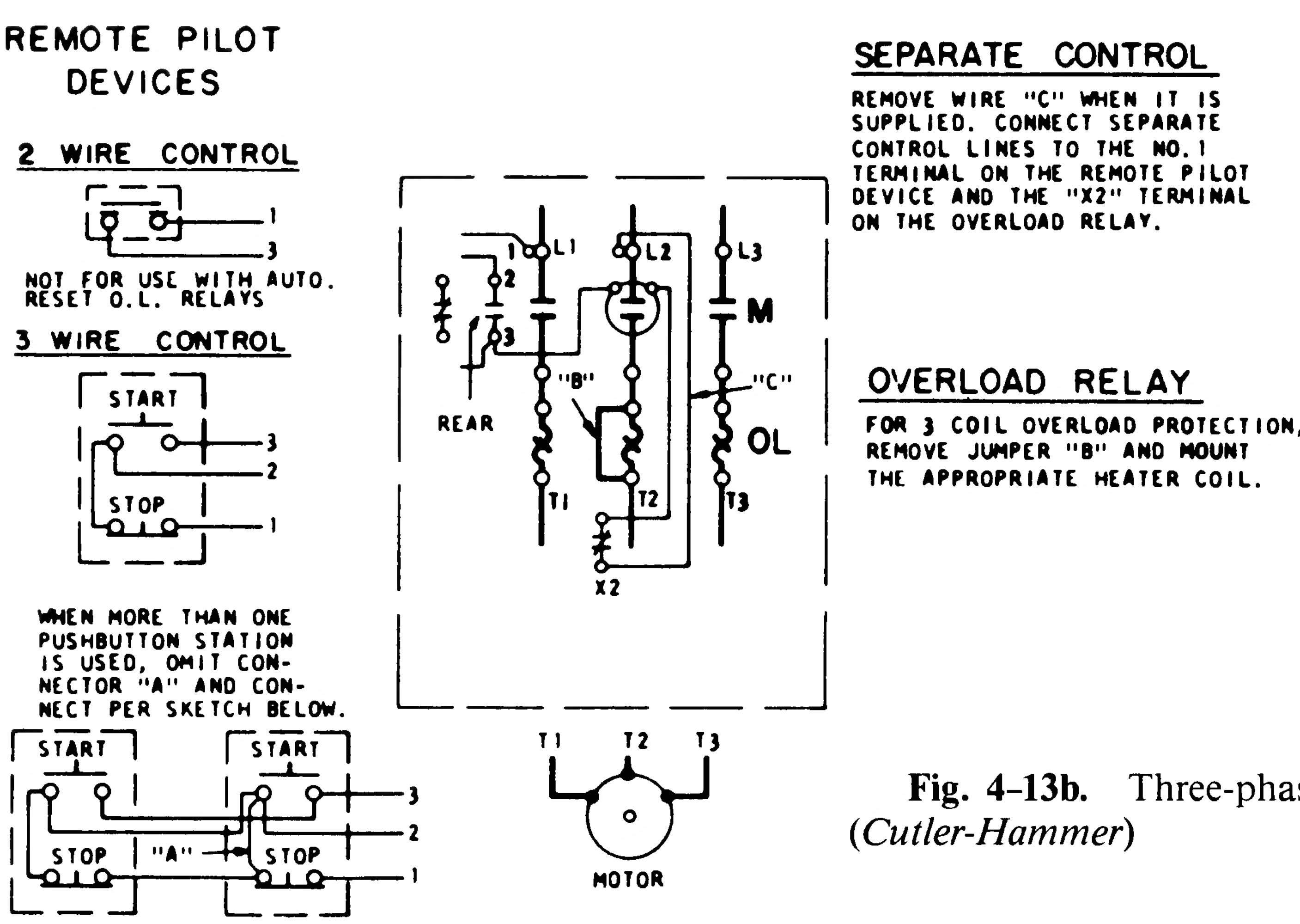


Fig. 4-13b. Three-phase starter. (*Cutler-Hammer*)

Figures 4–13a; 4–13b

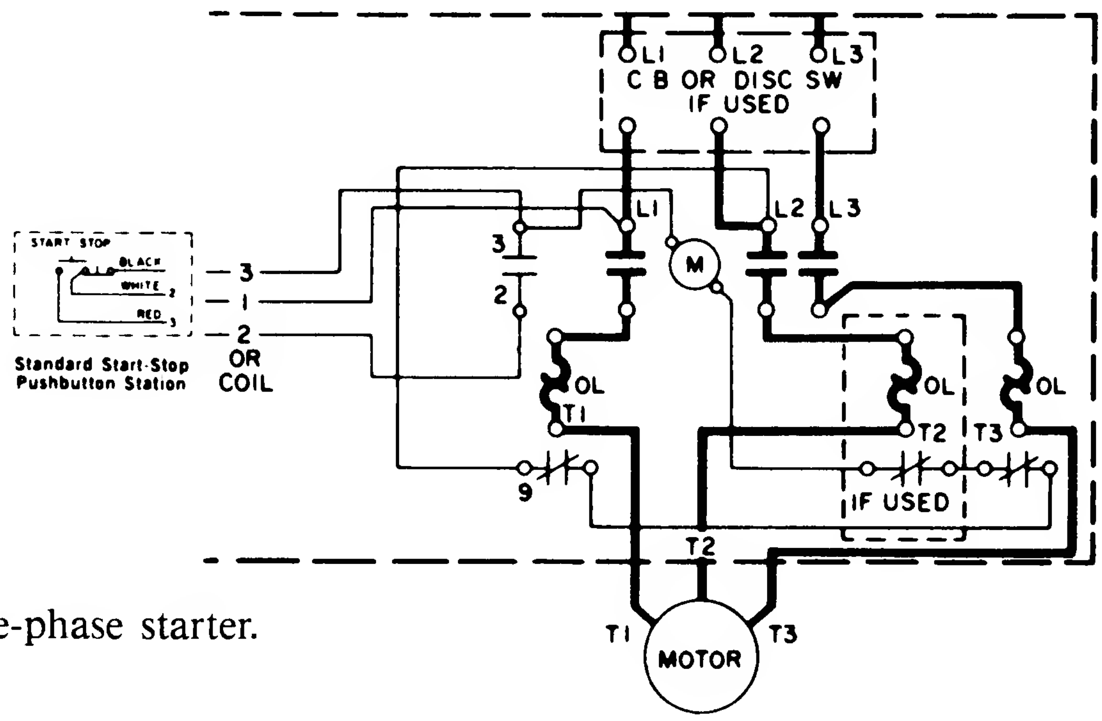


Fig. 4-13c. Three-phase starter. (*General Electric Co.*)

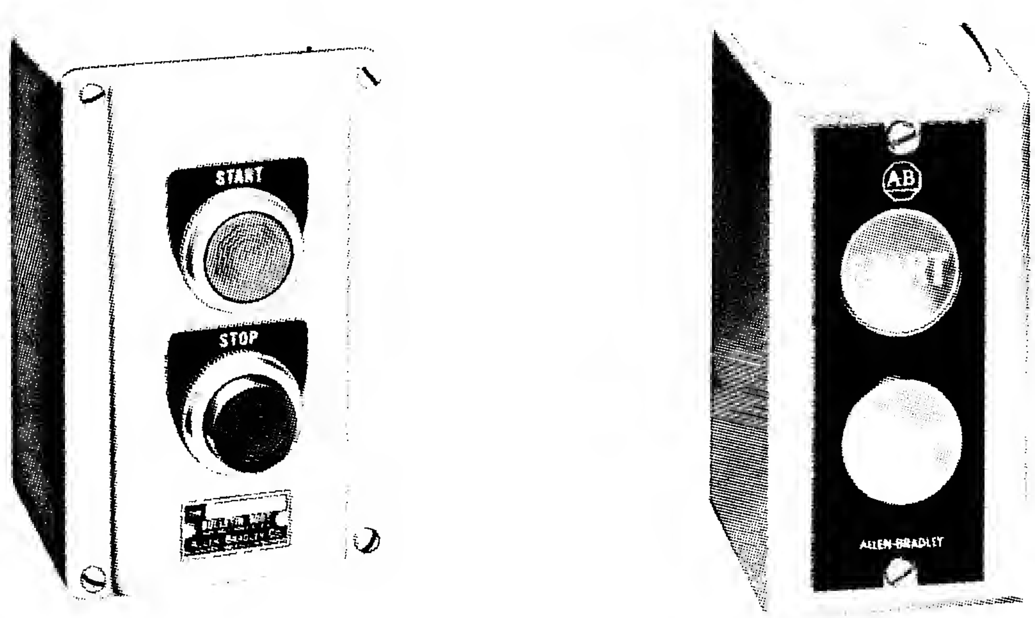


Fig. 4-14. Start-stop stations. (*Allen-Bradley Co.*)

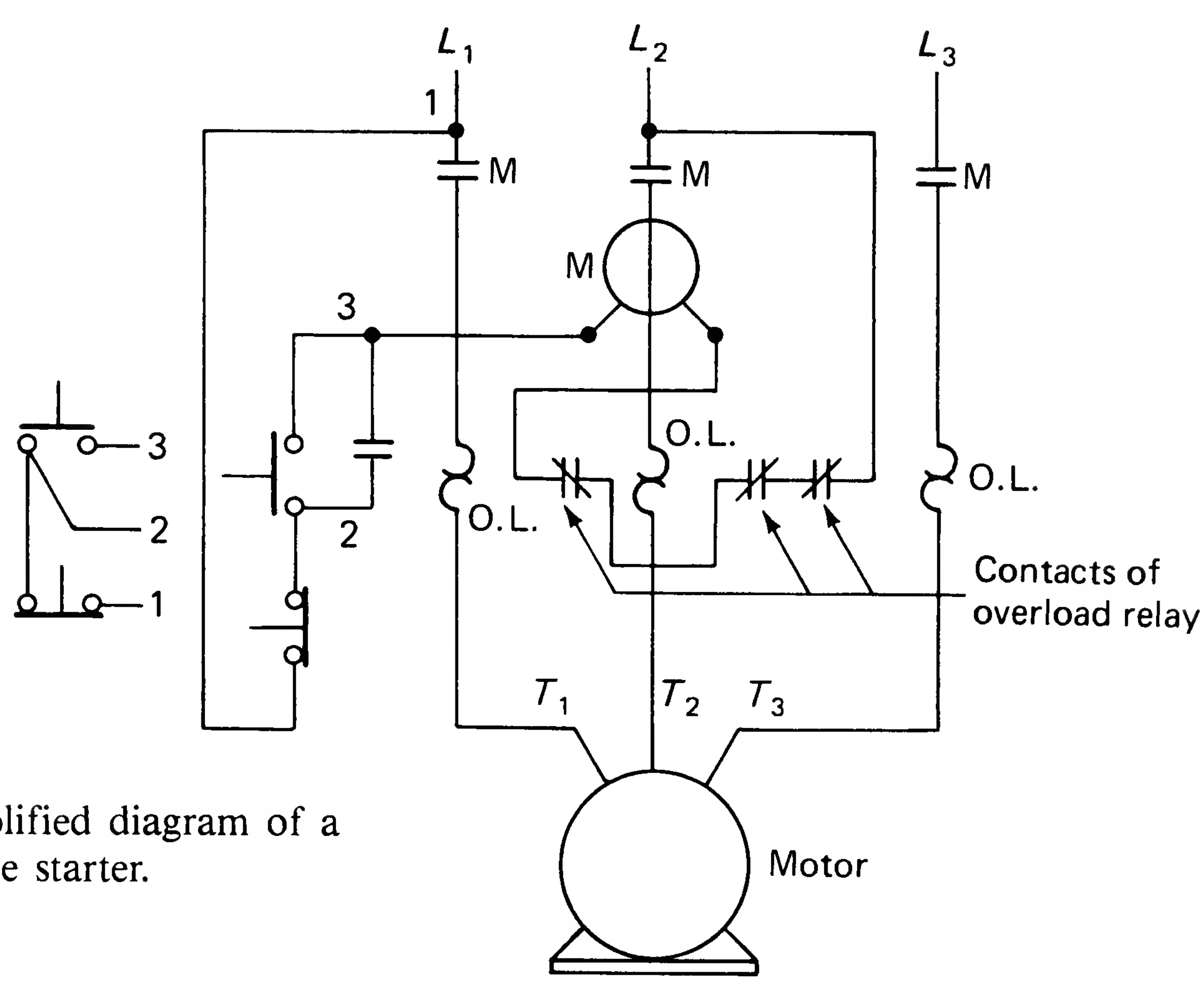


Fig. 4-15. A simplified diagram of a magnetic across-the-line starter.

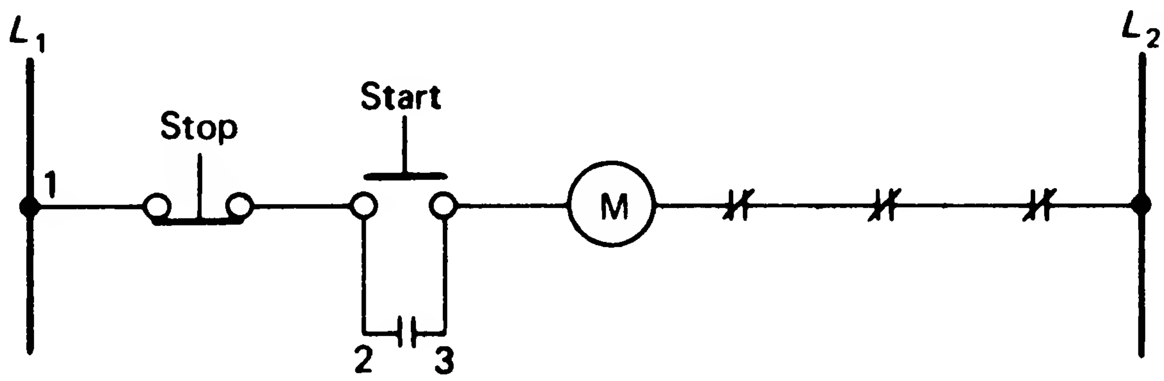


Fig. 4-16. Line diagram of a control circuit.

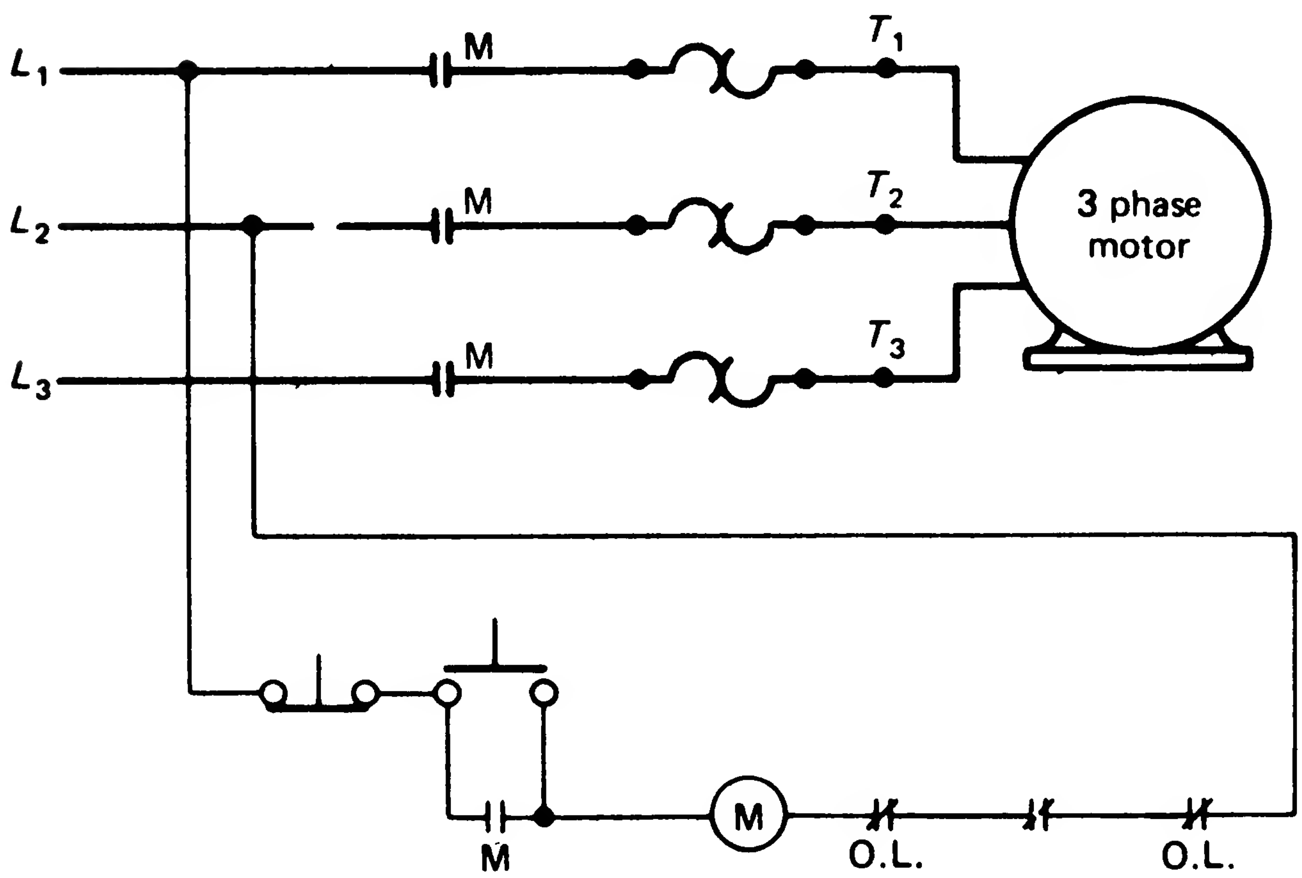


Fig. 4-17. A line diagram of a magnetic across-the-line starter.

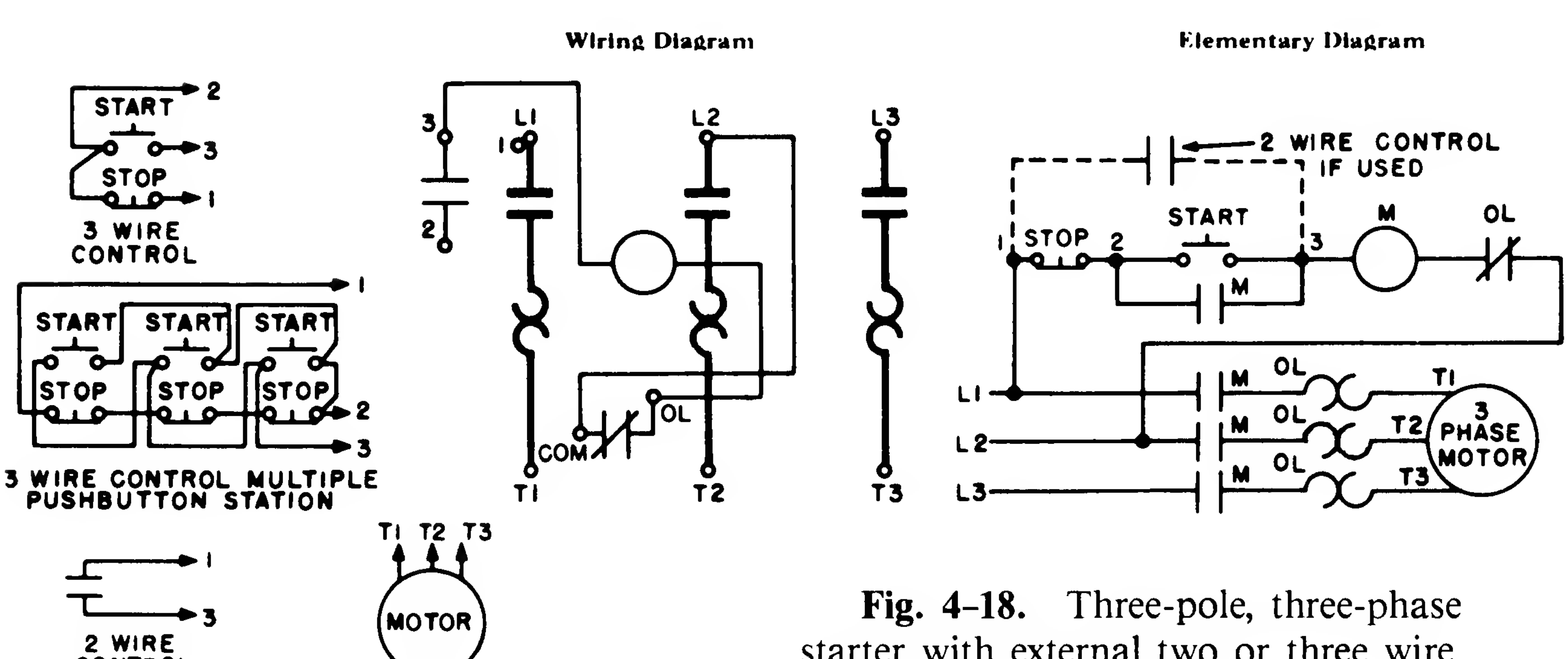


Fig. 4-18. Three-pole, three-phase starter with external two or three wire control. (*Square D Co.*)

Figures 4-16; 4-17; 4-18

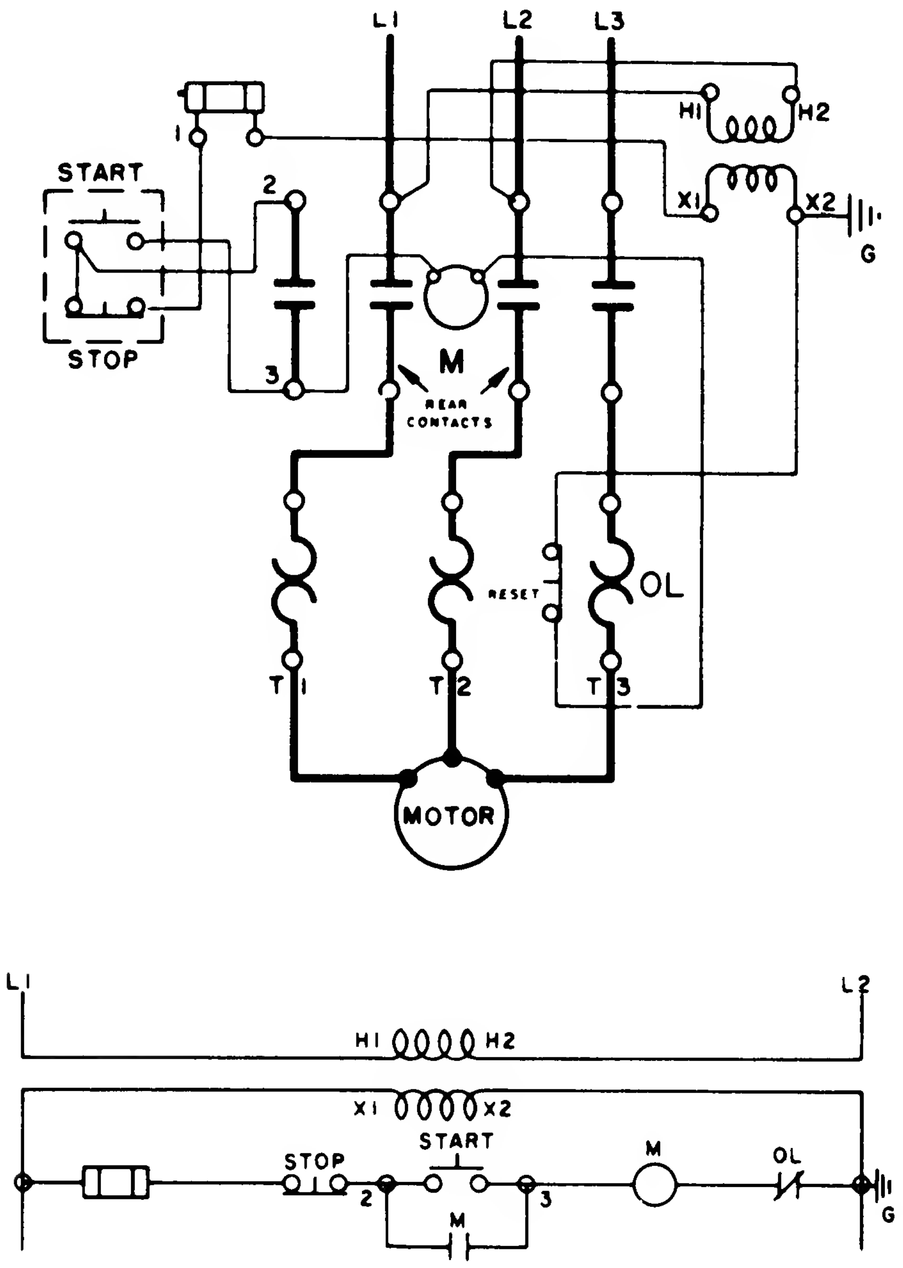


Fig. 4-19. Three-phase starter with three-coil thermal O.L. relay and step down control transformer in control circuits. (*Cutler-Hammer*)

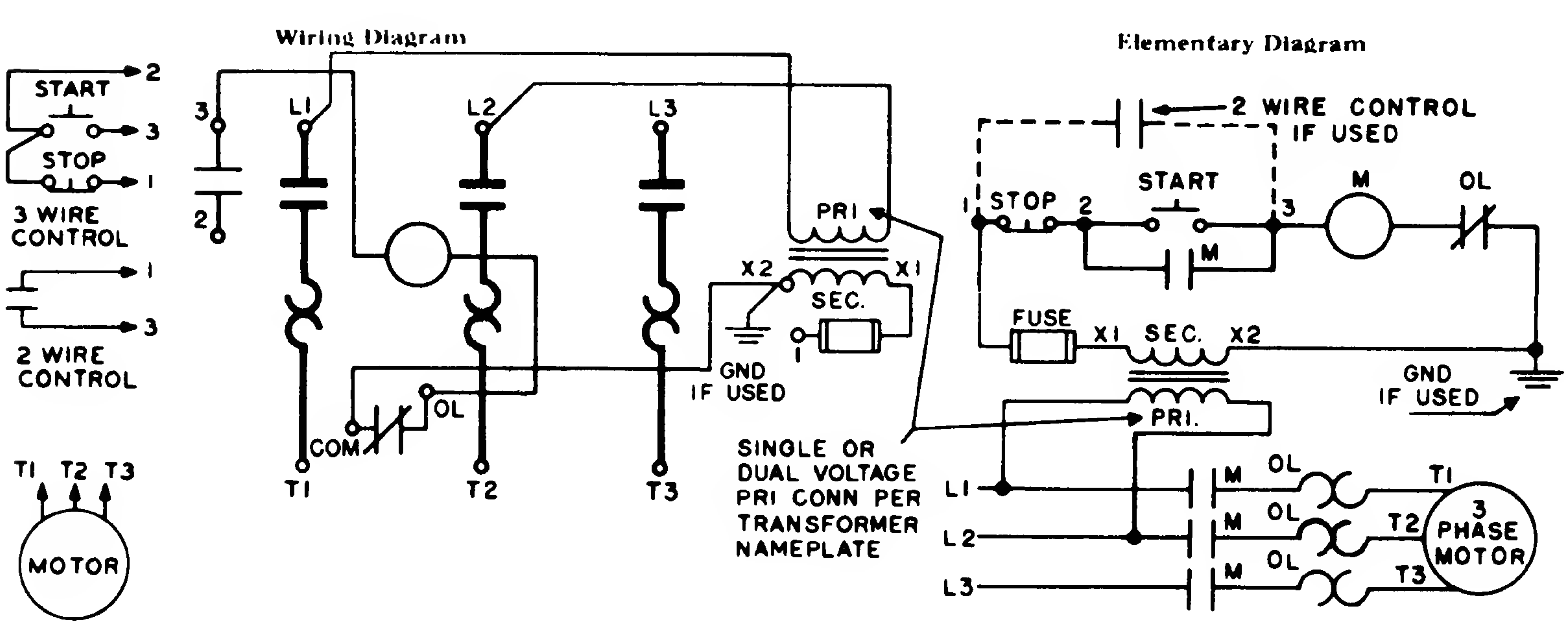


Fig. 4-20. Three-phase starter with control-circuit transformer and secondary fuse. (*Square D Co.*)

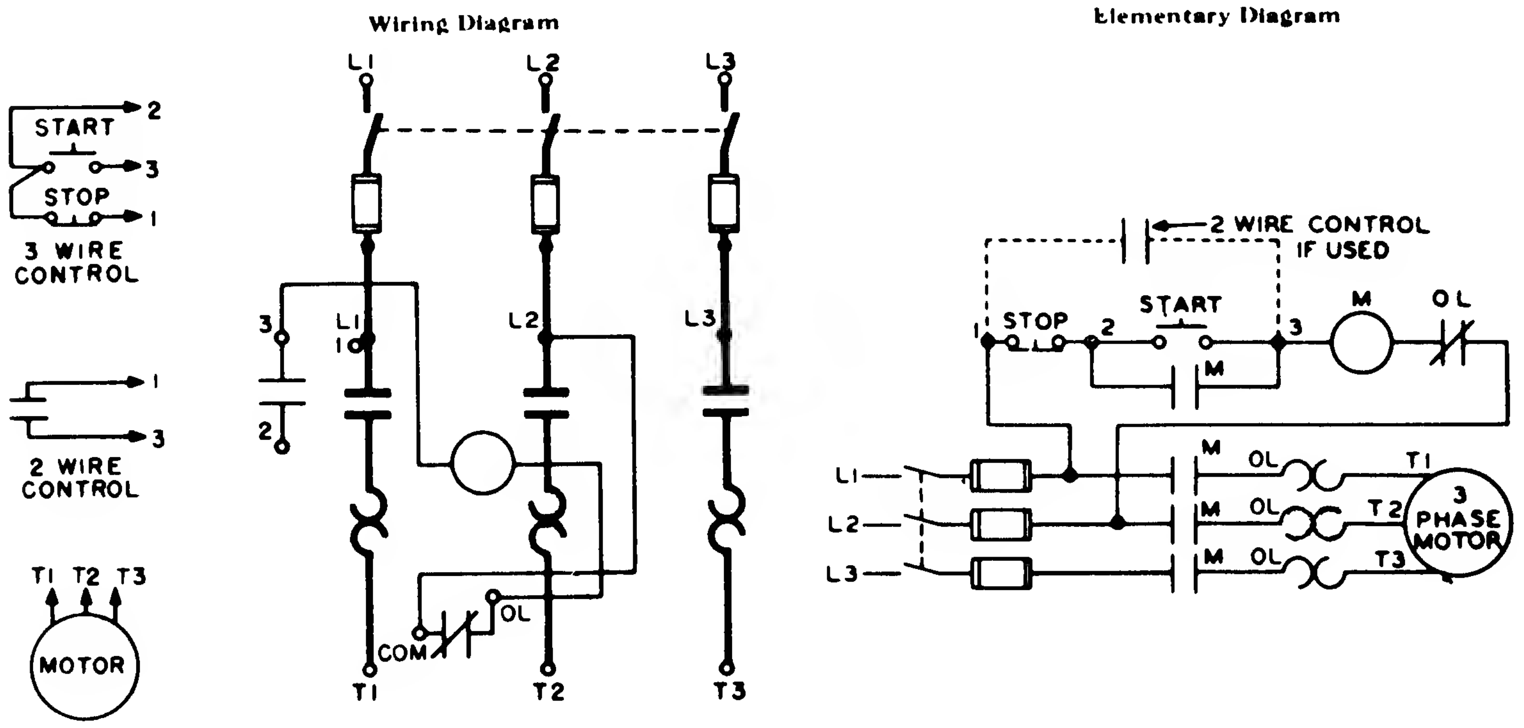


Fig. 4-21. Combination starters with fusible disconnect switch. (*Square D Co.*)

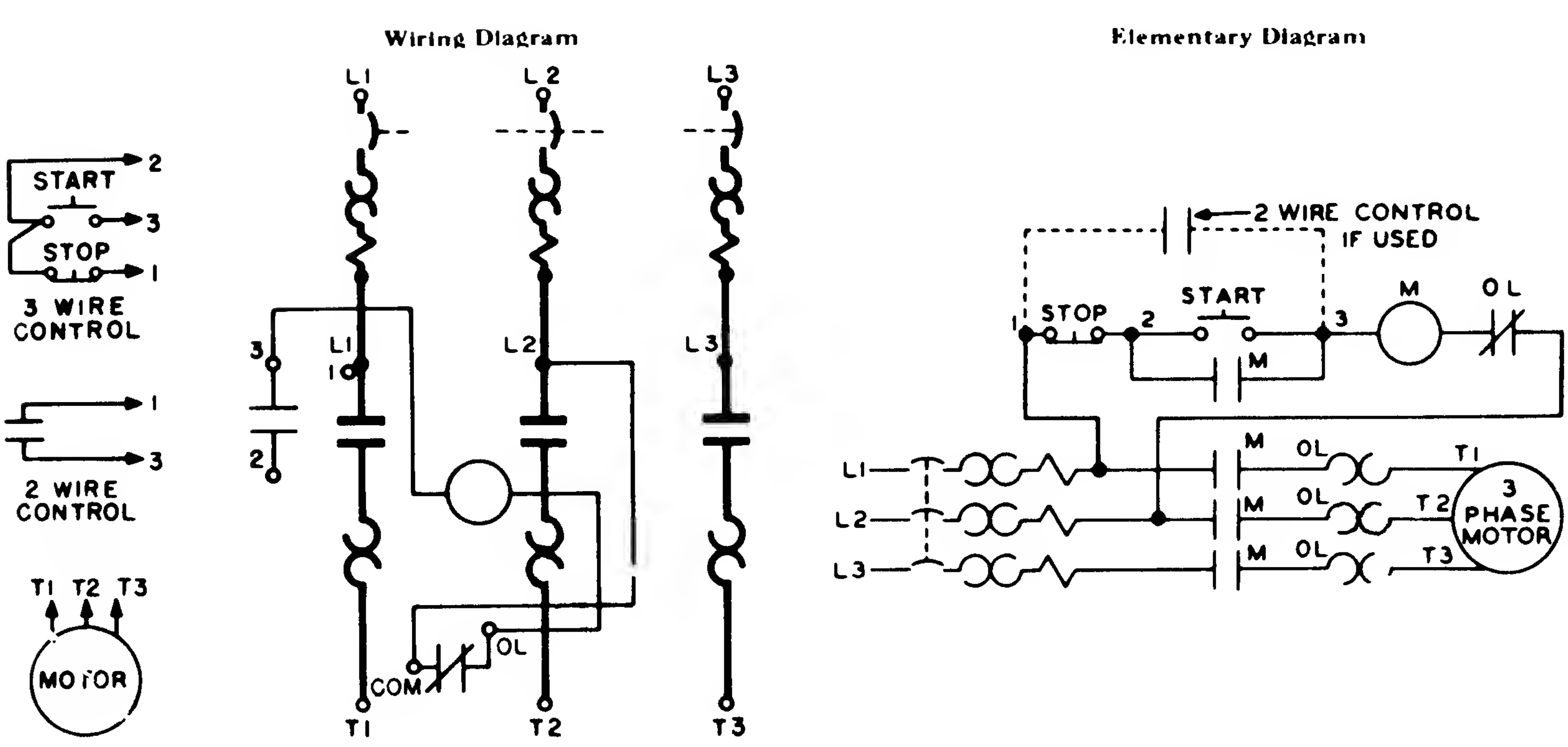


Fig. 4-22. Combination starters with thermal magnetic circuit breaker. (*Square D Co.*)

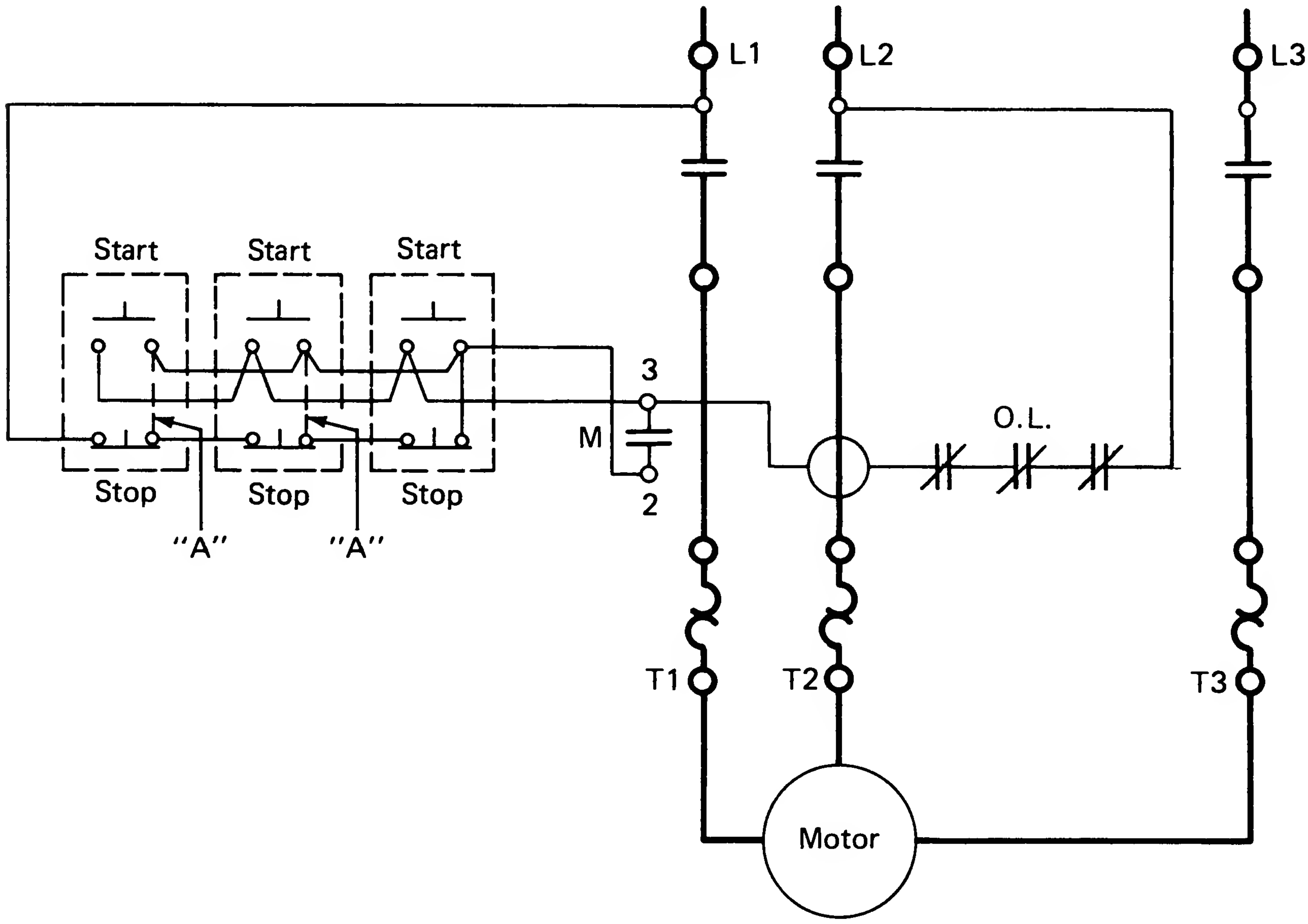


Fig. 4–23. A magnetic switch controlled by three START-STOP stations. (*Allen-Bradley Co.*)

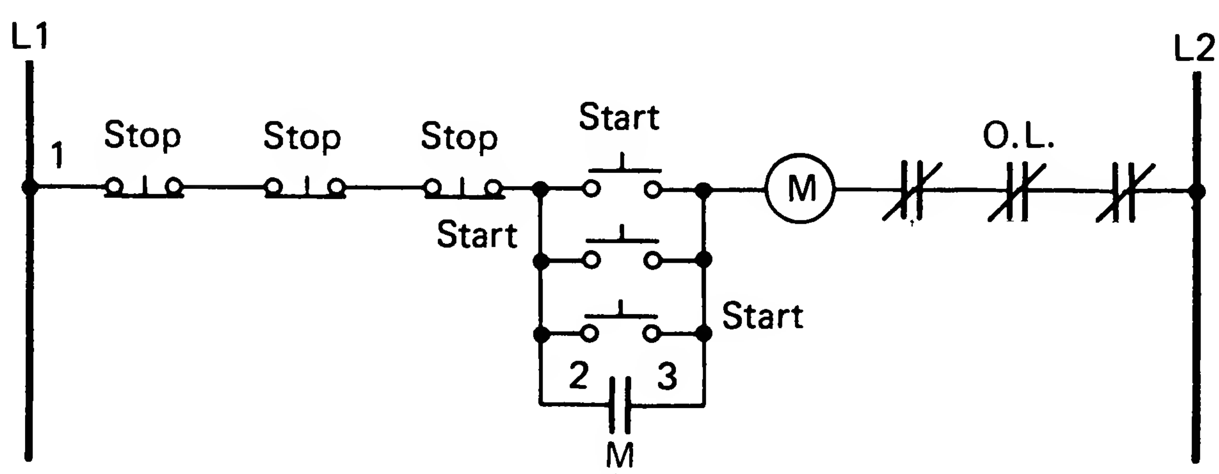


Fig. 4–24. A control circuit for three START-STOP stations. (*Allen-Bradley Co.*)

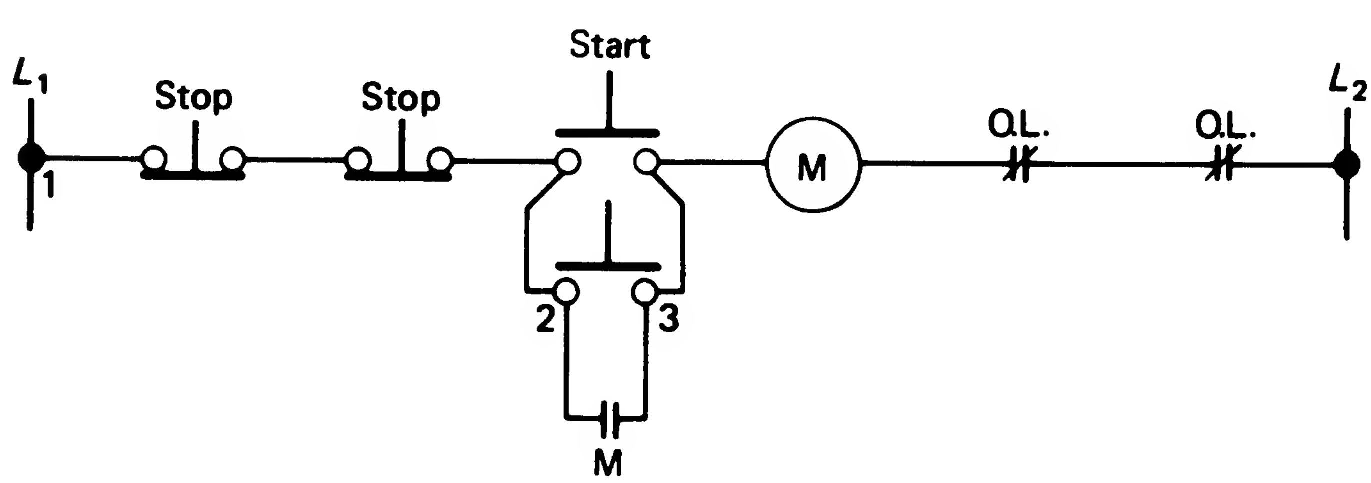


Fig. 4–25. A control circuit for two START-STOP stations.

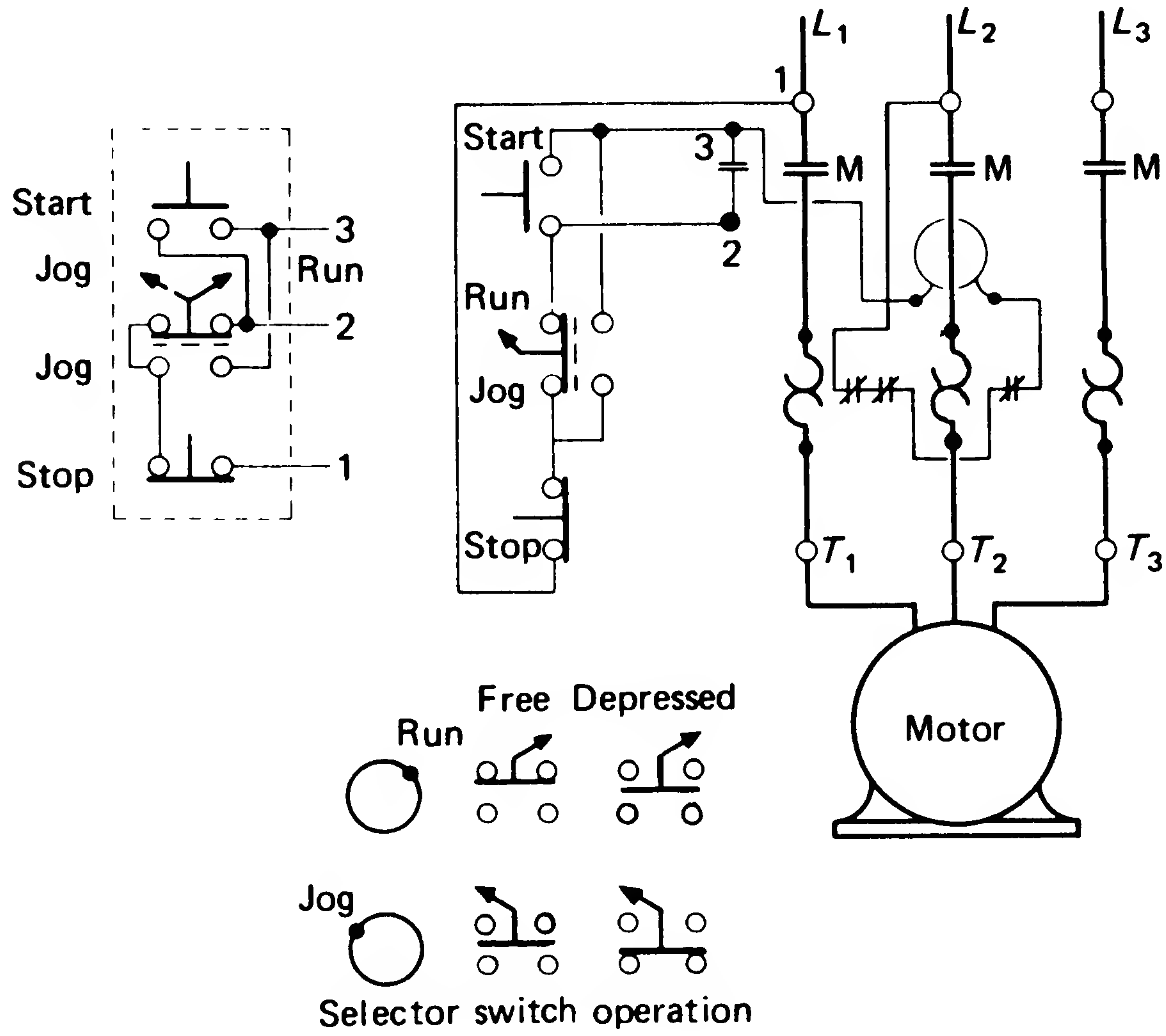


Fig. 4–26. A START-JOG-STOP station with selector push button, connected to a magnetic switch.

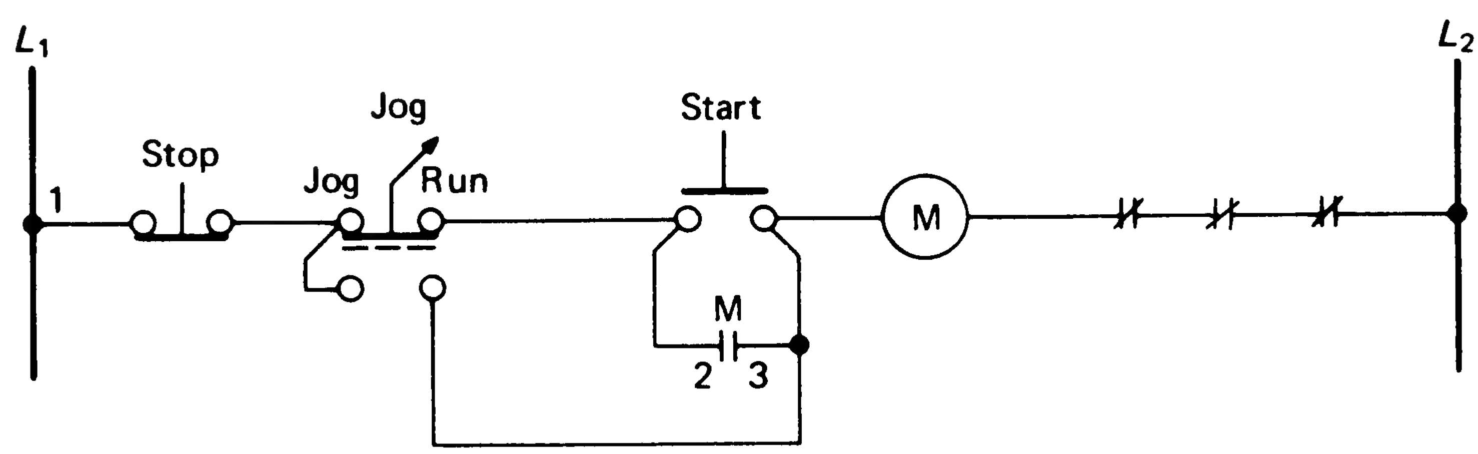


Fig. 4–27. START-JOG-STOP station with selector push button.

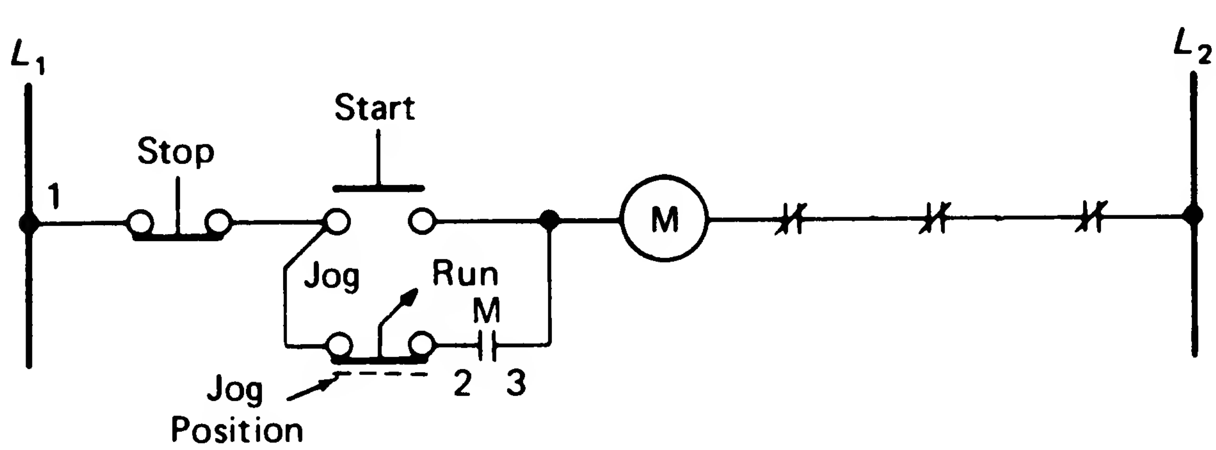


Fig. 4–28. Jogging with push-turn selector switch.

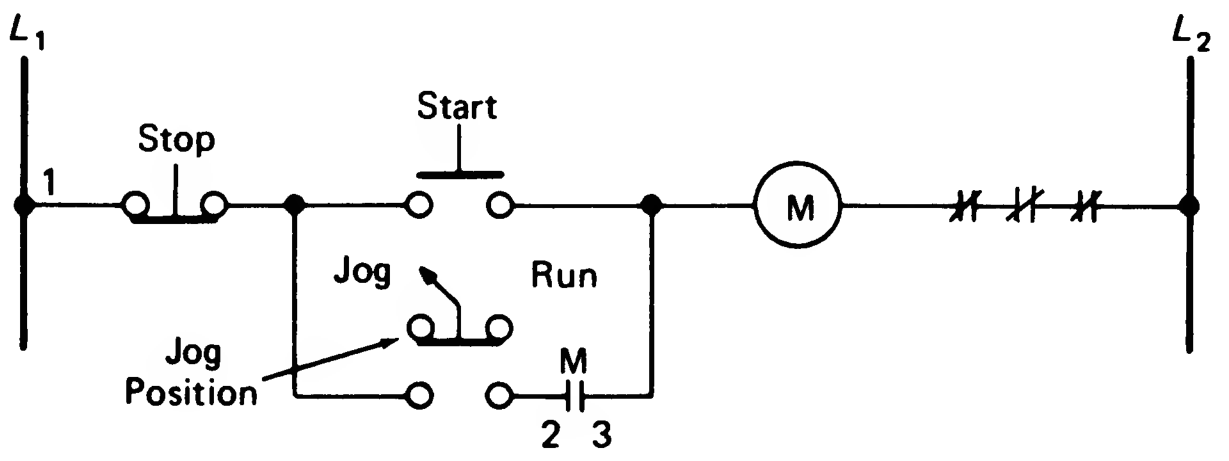


Fig. 4–29. Jogging with a selector switch.

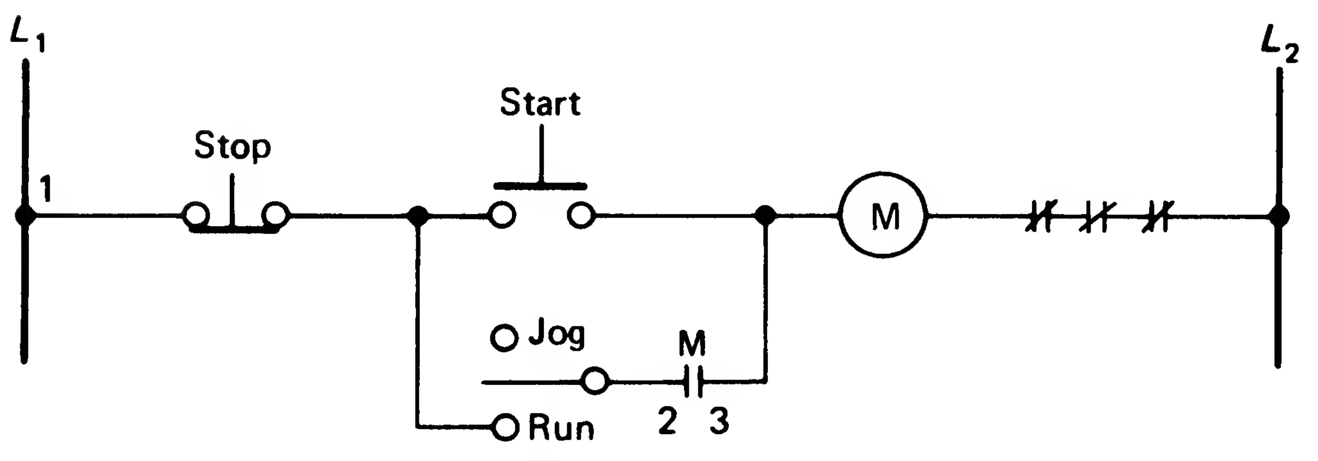
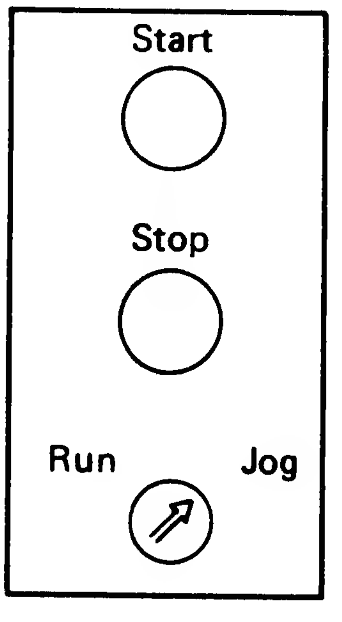


Fig. 4–30. Control circuit with JOG-RUN selector switch.

Fig. 4–31. A panel of a station in which the START button can be used for inching or jogging.



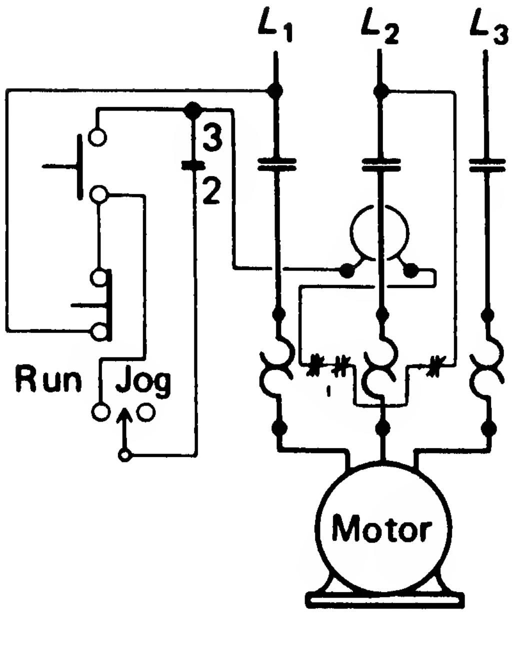


Fig. 4–32. Magnetic switch with JOG-RUN selector switch.

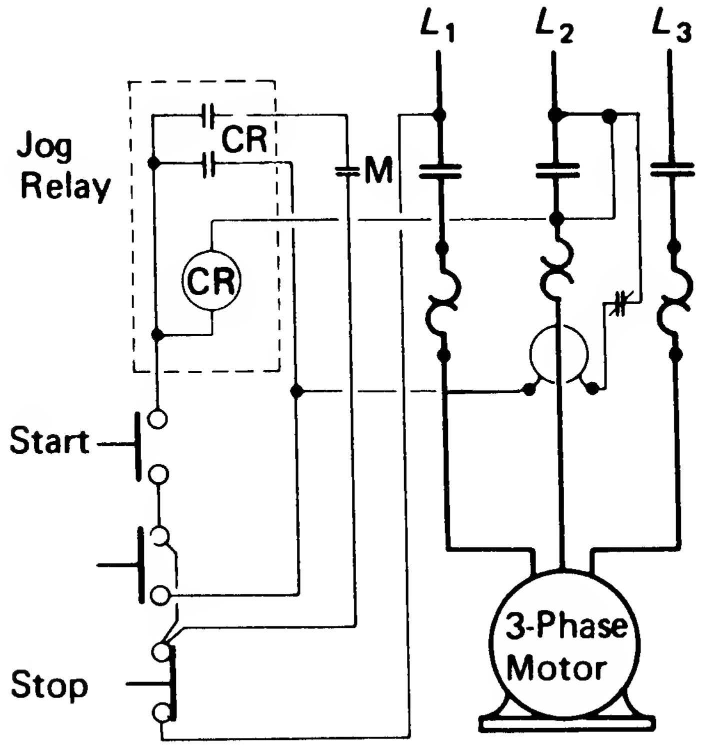


Fig. 4–33. A magnetic switch operated by a START-JOG-STOP station with a jog-relay attachment.

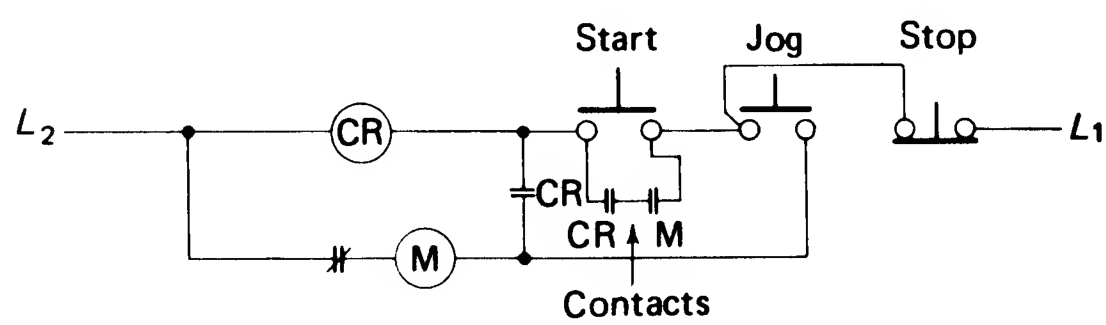


Fig. 4–34. An elementary diagram of Fig. 4-33.

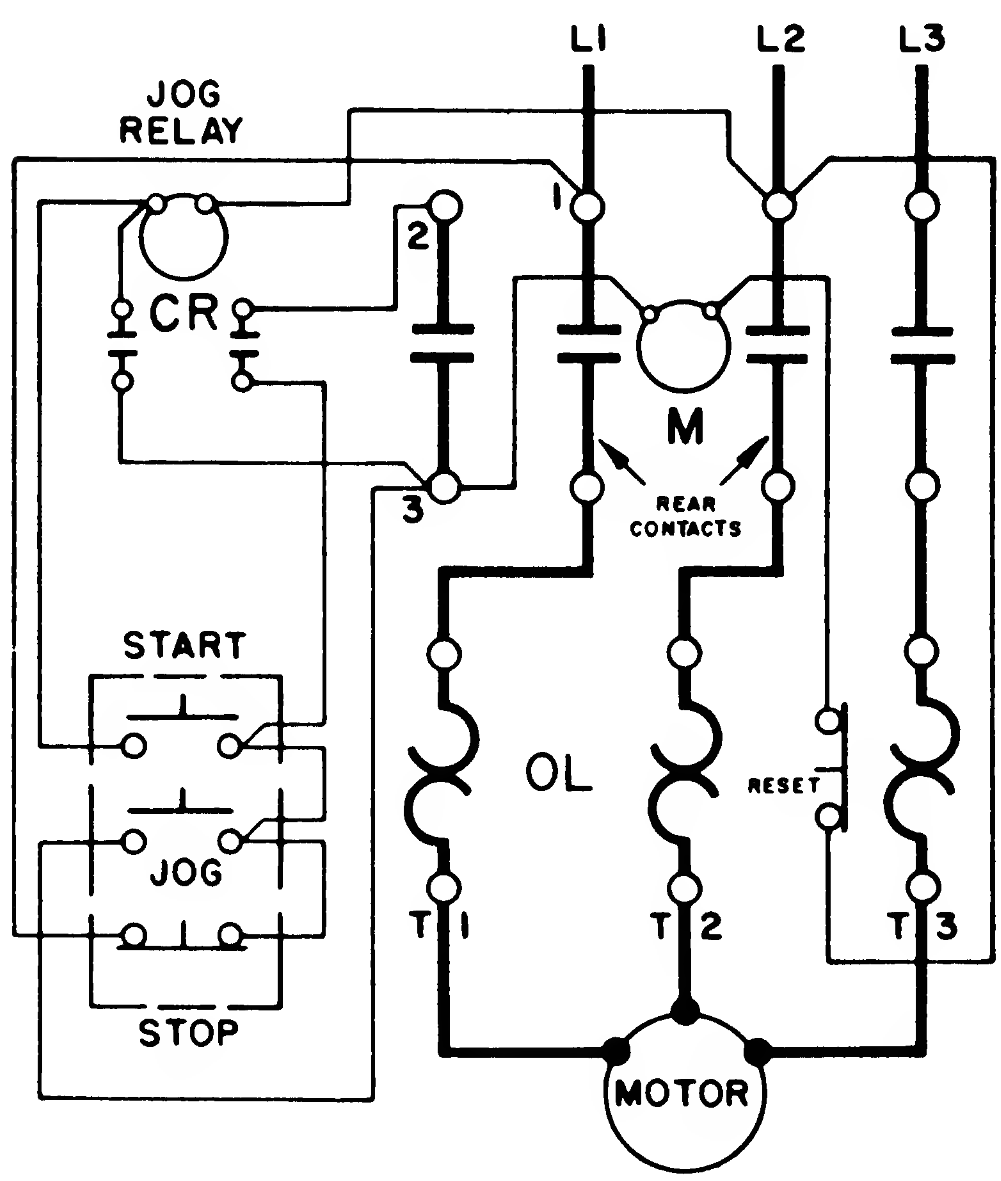


Fig. 4–35. A jog relay connected to a magnetic switch.

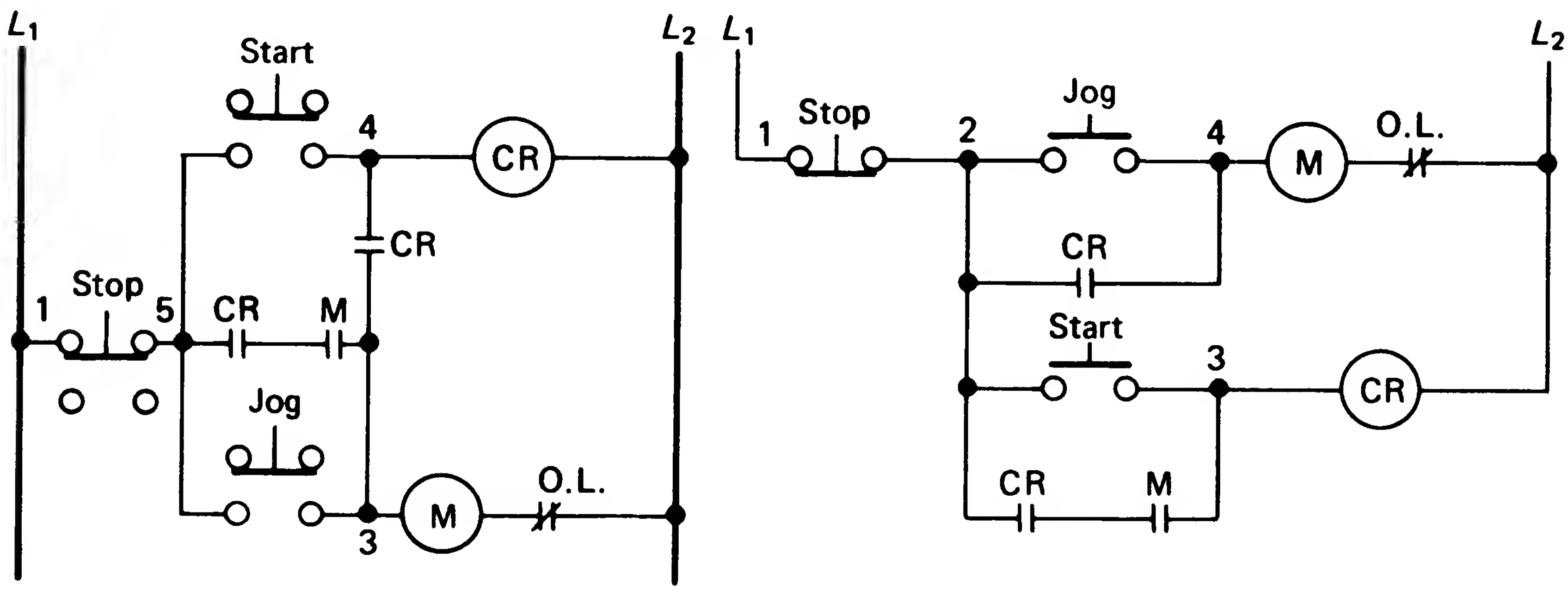


Fig. 4–36. Control circuits of START-JOG-STOP button connected to a jog relay.

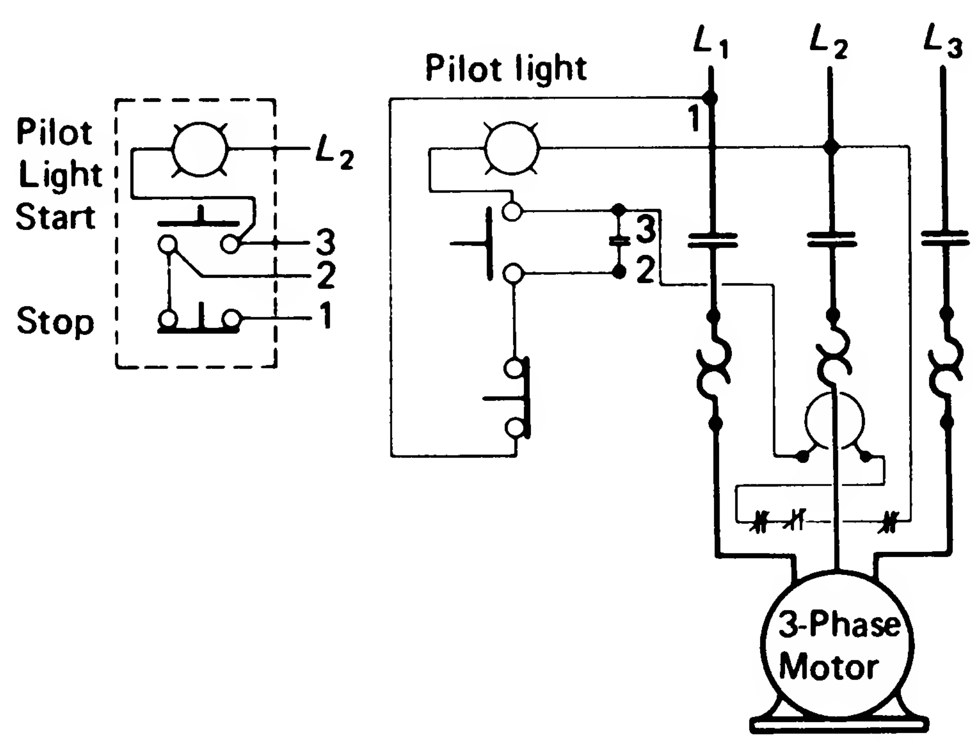


Fig. 4–37. Push button station with pilot light connected to a three-phase magnetic starter.

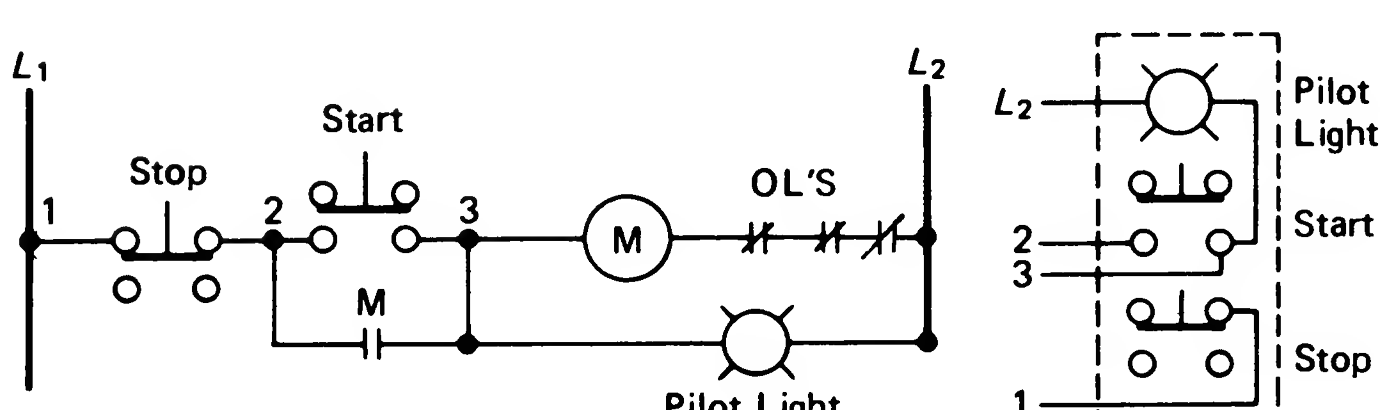


Fig. 4–38. A simple control circuit of a START-STOP station with a pilot light.

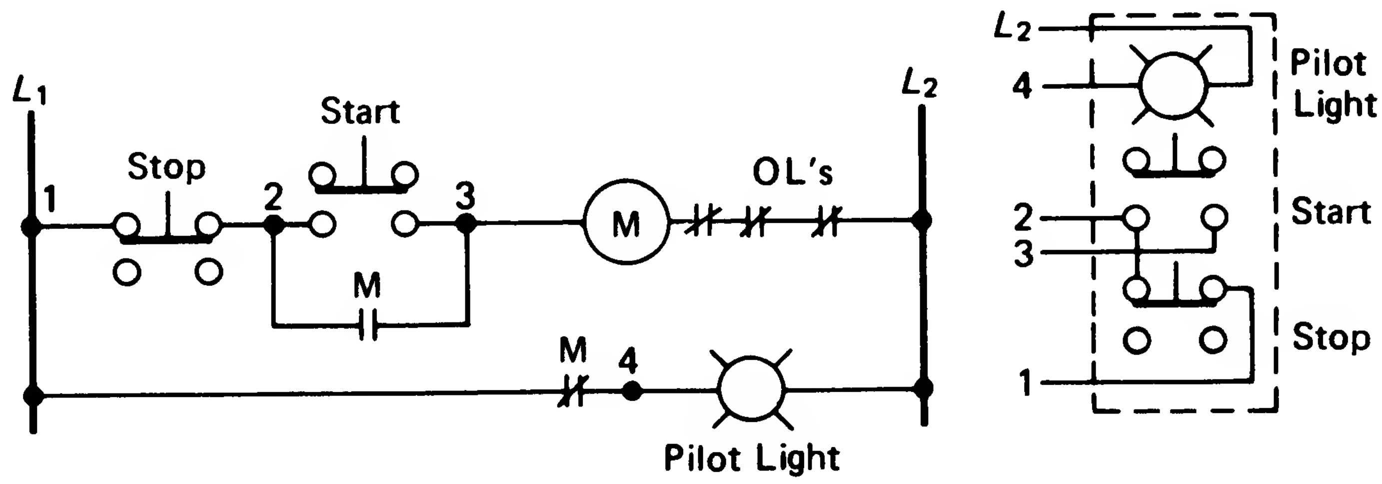


Fig. 4-39. Pilot light indicates when motor is not running. Normally closed contact M must be added to the starter.

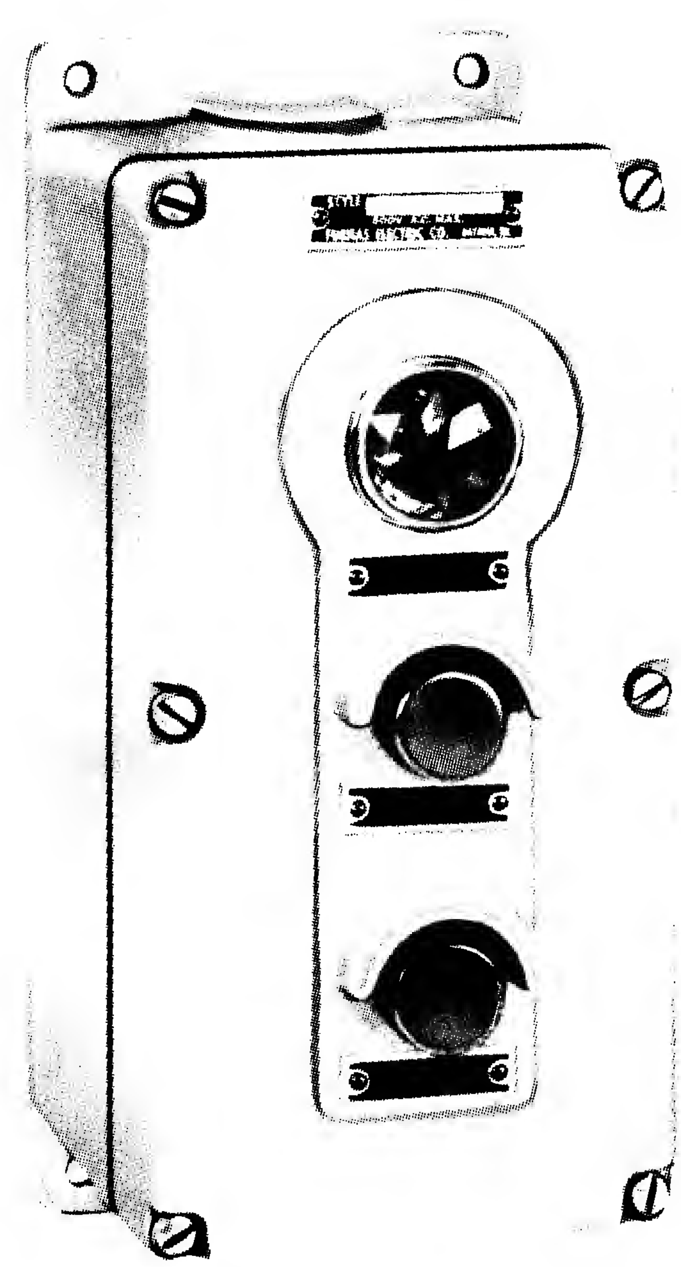


Fig. 4-40. Station with pilot light. (*Furnas Electric Co.*)

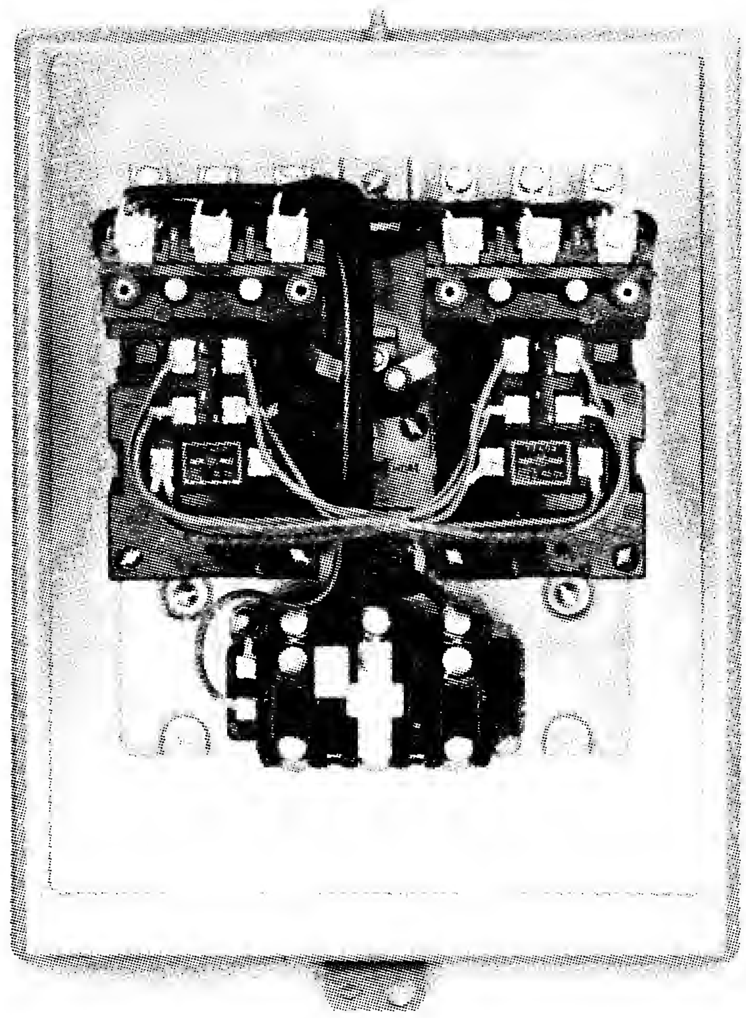


Fig. 4-41. An ac full-voltage magnetic reversing controller. (*Allen-Bradley Co.*)

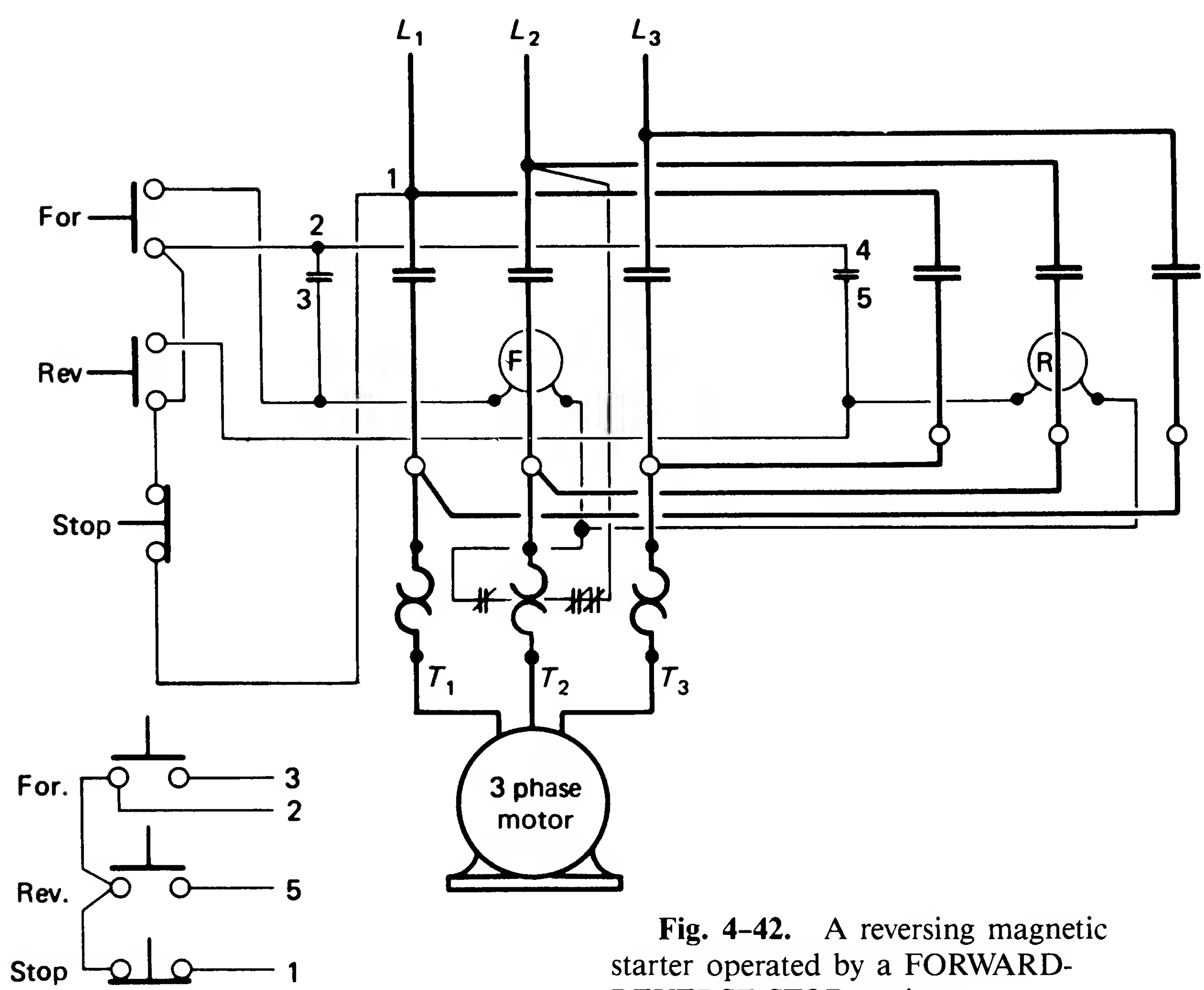


Fig. 4-42. A reversing magnetic starter operated by a FORWARD-REVERSE-STOP station.

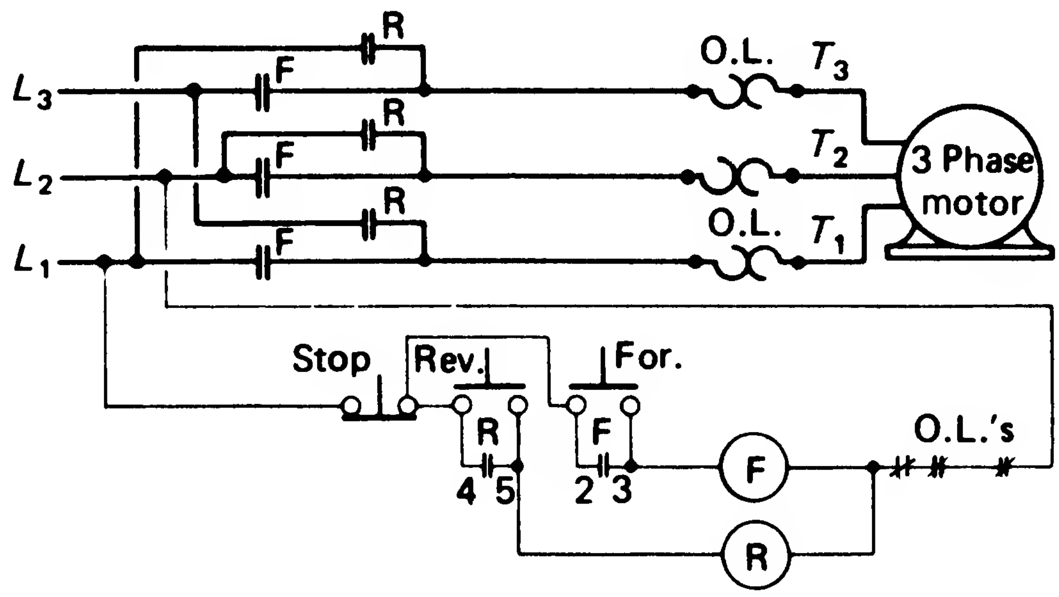


Fig. 4-43. An elementary diagram of **Fig. 4-42.**

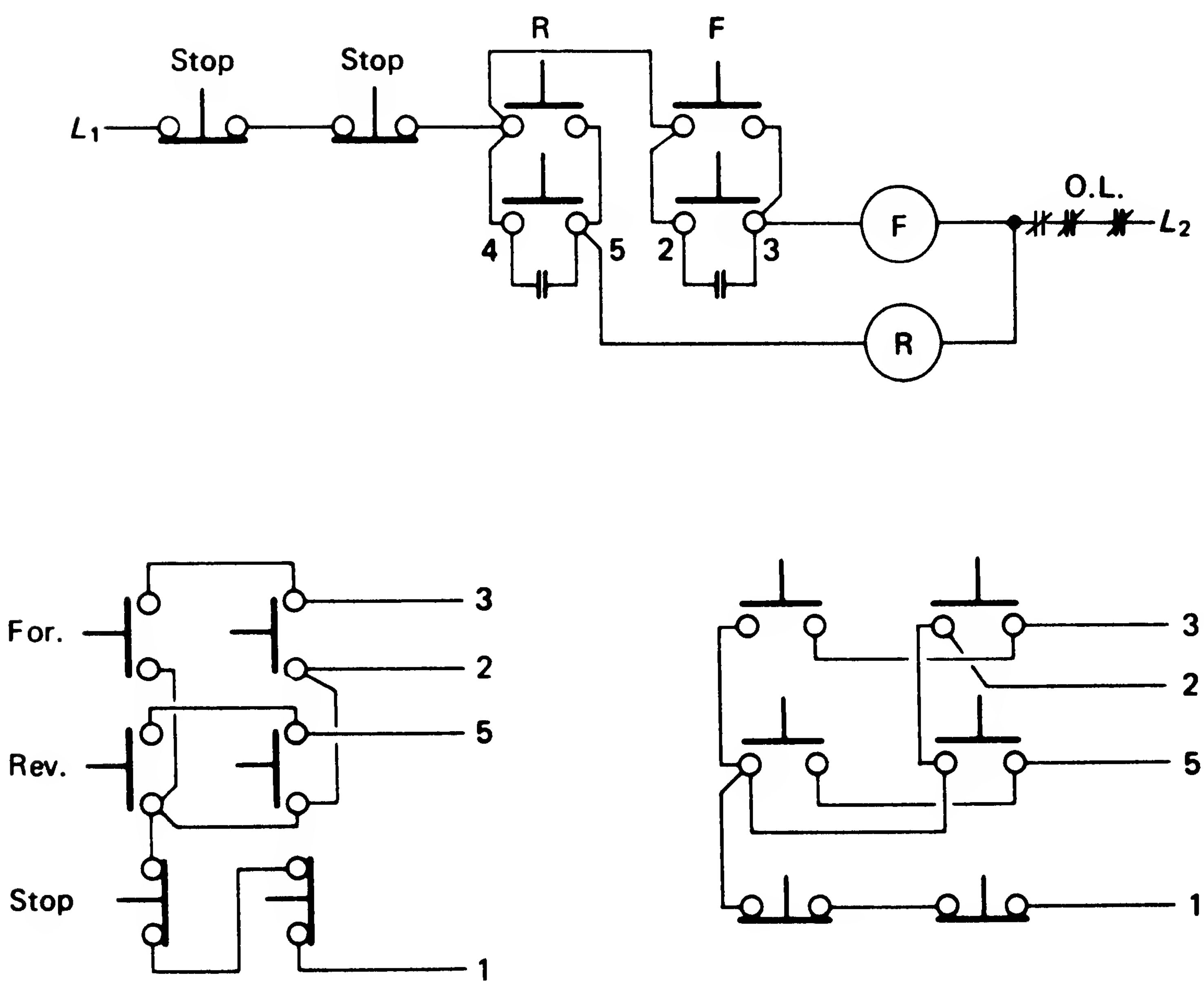


Fig. 4-44. Connections for two FORWARD-REVERSE-STOP stations to a reversing magnetic switch.

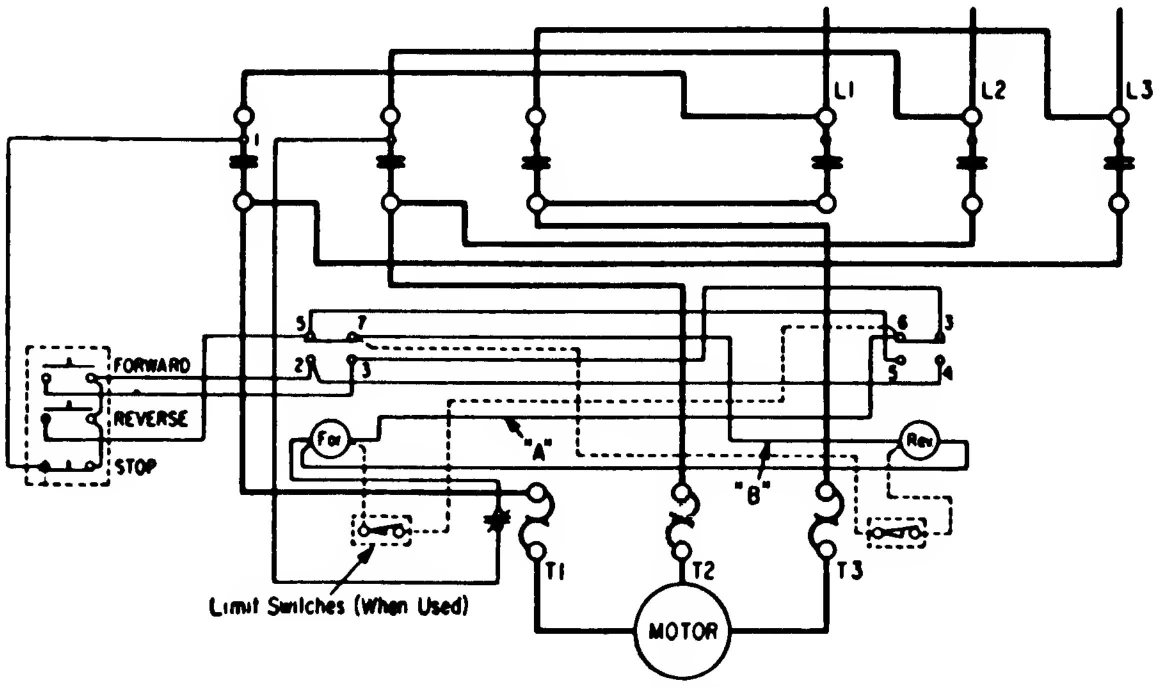


Fig. 4–45. Reversing magnetic starter with electrical interlock. (*Allen-Bradley Co.*)

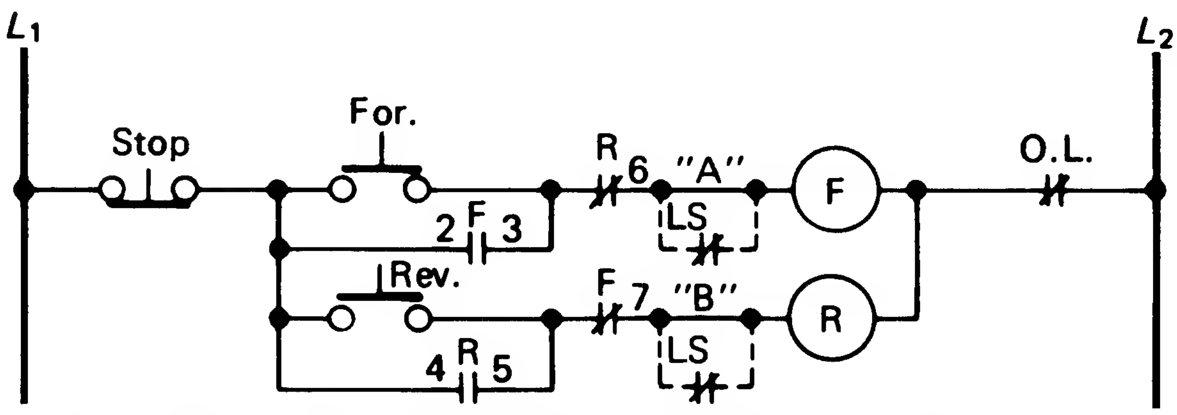


Fig. 4–46. Line diagram of control circuits of **Fig. 4–45**.

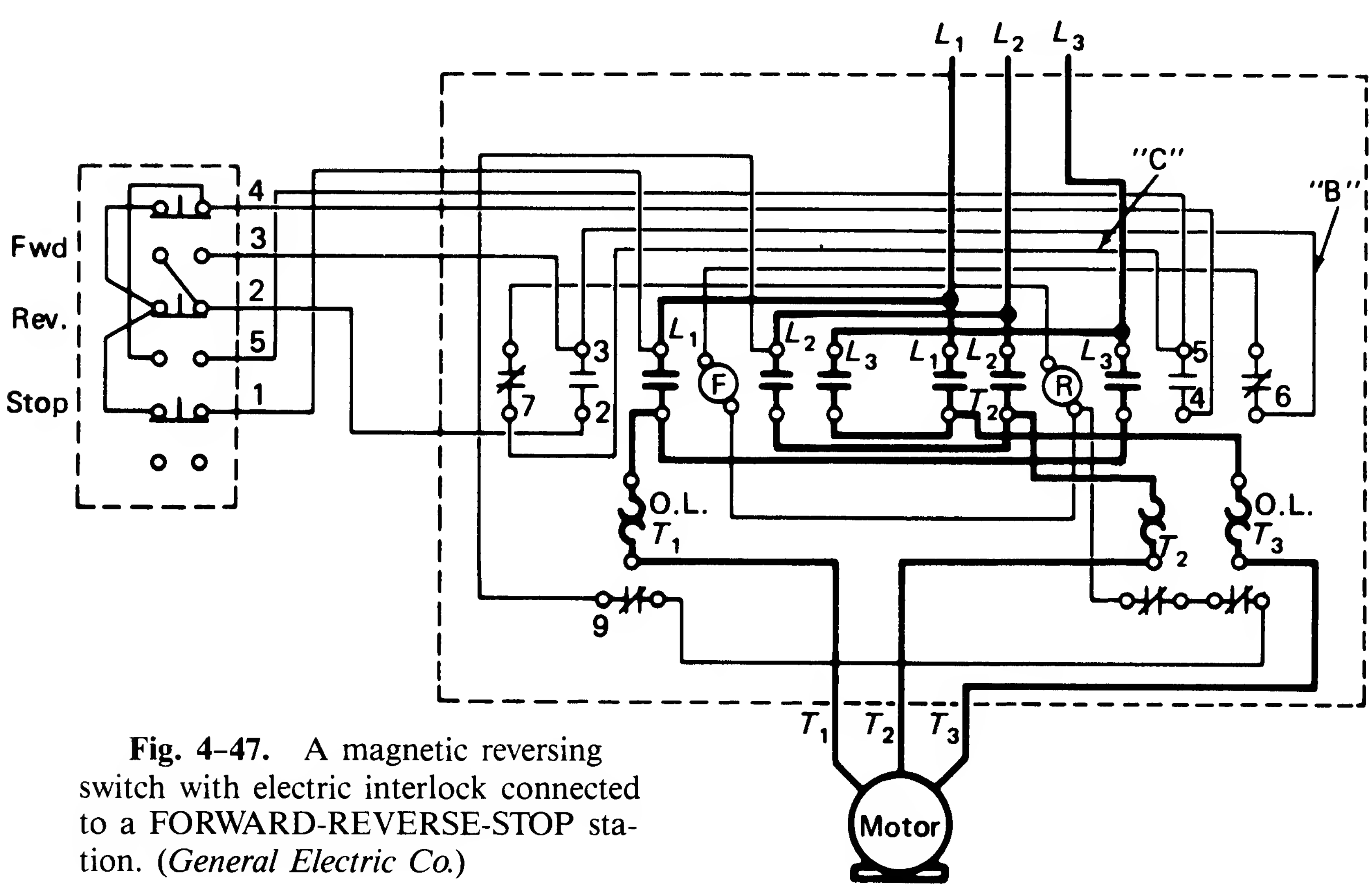


Fig. 4–47. A magnetic reversing switch with electric interlock connected to a FORWARD-REVERSE-STOP station. (*General Electric Co.*)

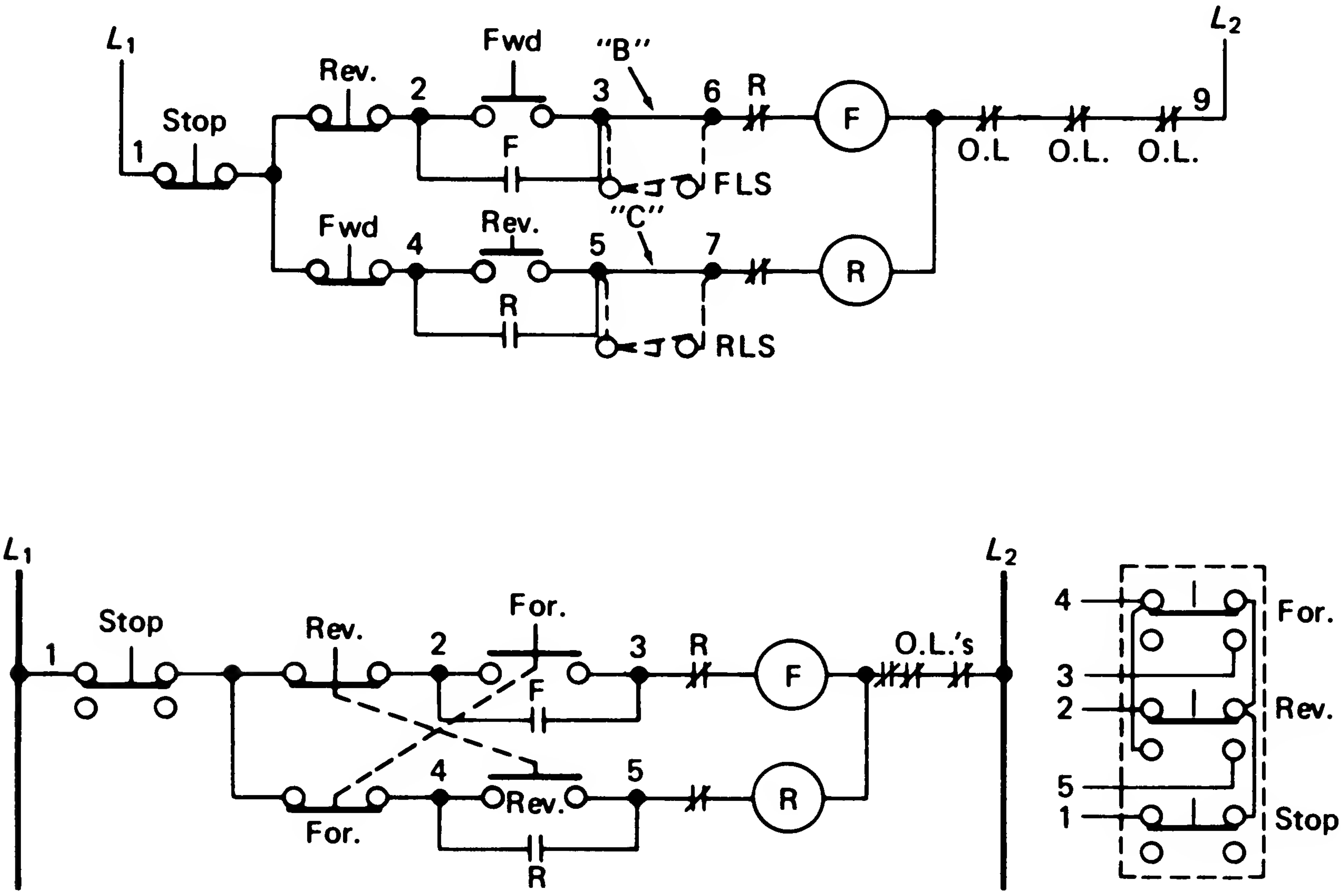


Fig. 4–48. Line diagram control circuits of magnetic reversing switch with electric interlock. *B* and *C* are used if limit switches are not used.

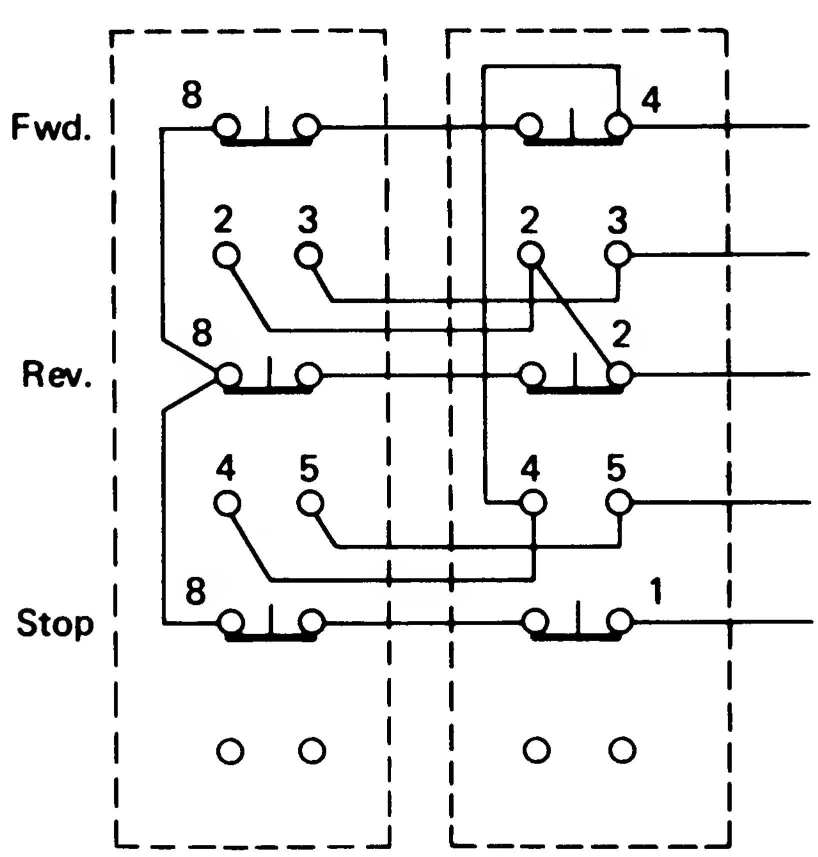


Fig. 4–49. Two FORWARD-REVERSE-STOP stations connected to fermis immediately reversing without pressing STOP button.

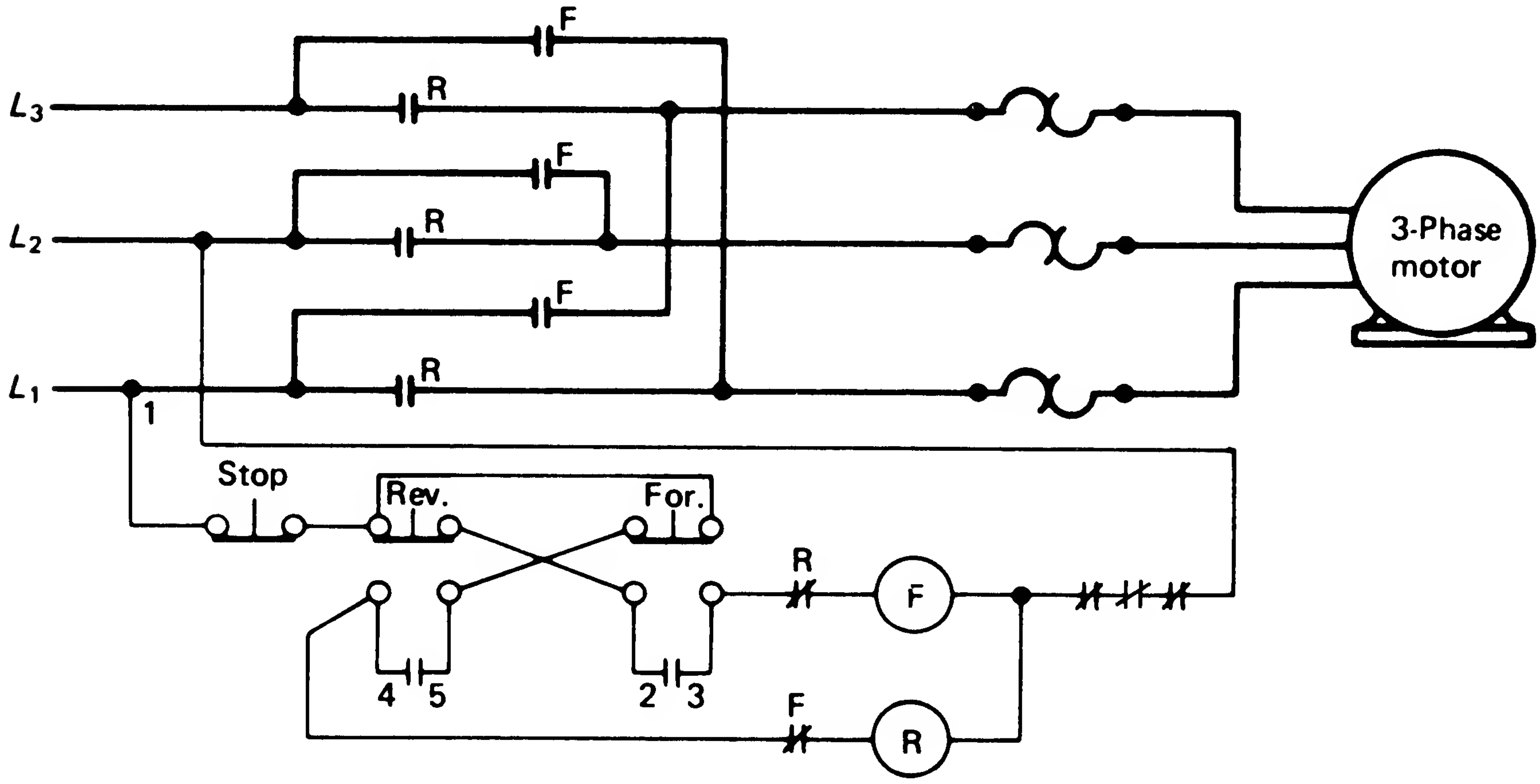


Fig. 4-50. An elementary diagram of a reversing magnetic starter with electrical interlocks.

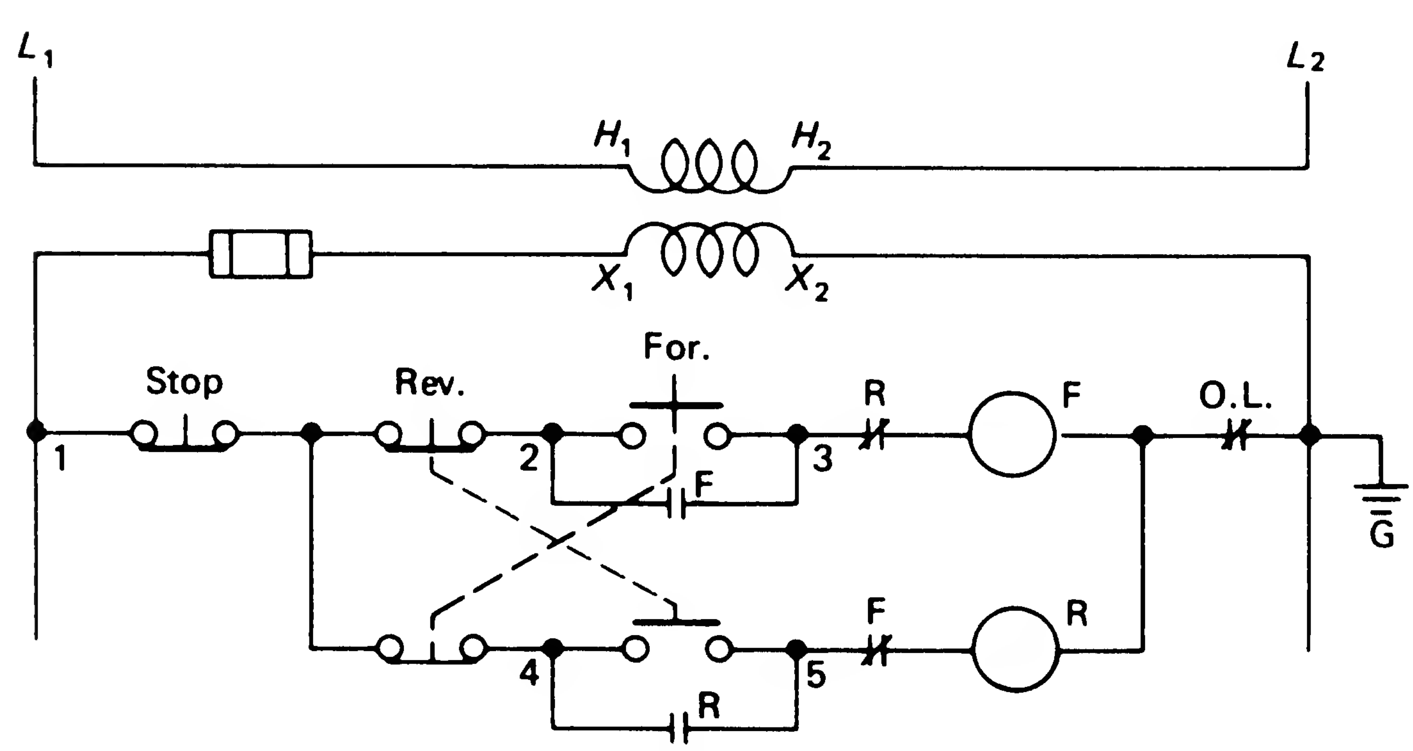


Fig. 4-51. Control circuit with step down transformer.

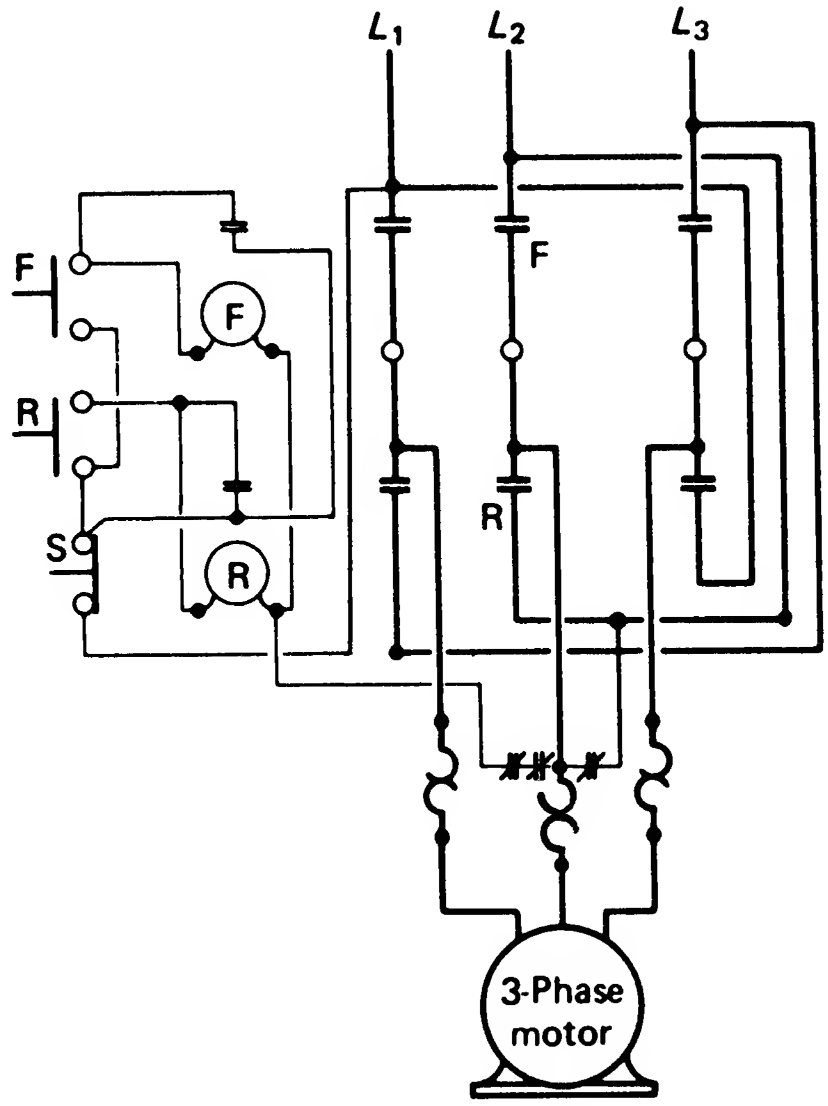


Fig. 4–52. A magnetic reversing switch in a vertical, instead of a horizontal, position.

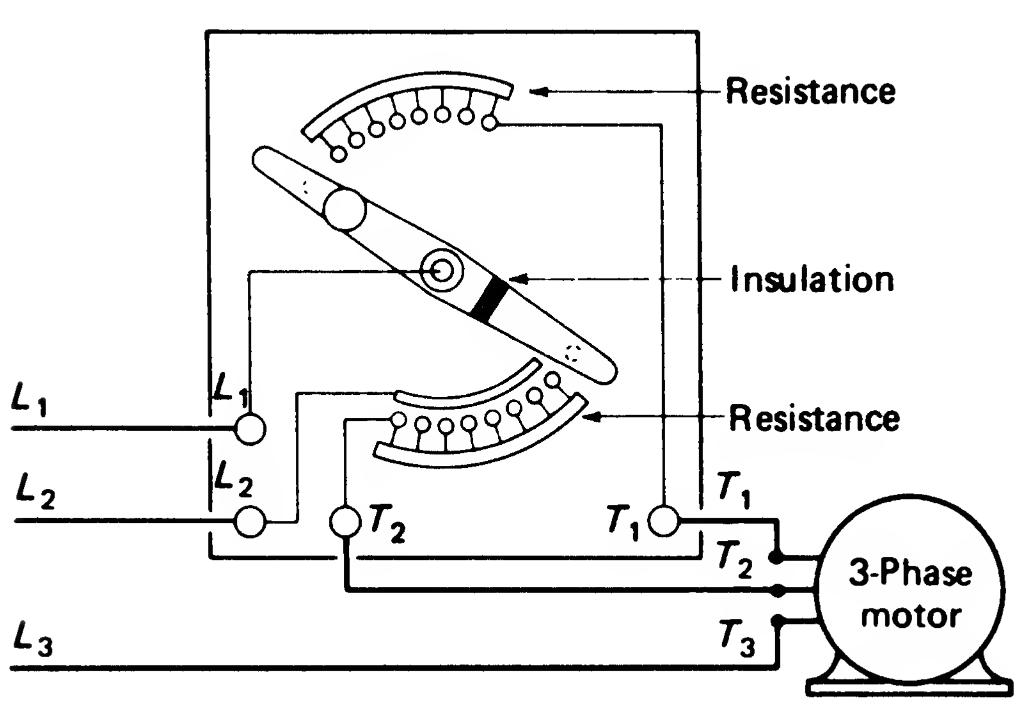


Fig. 4–53. A manual resistance starter of the rheostat type.

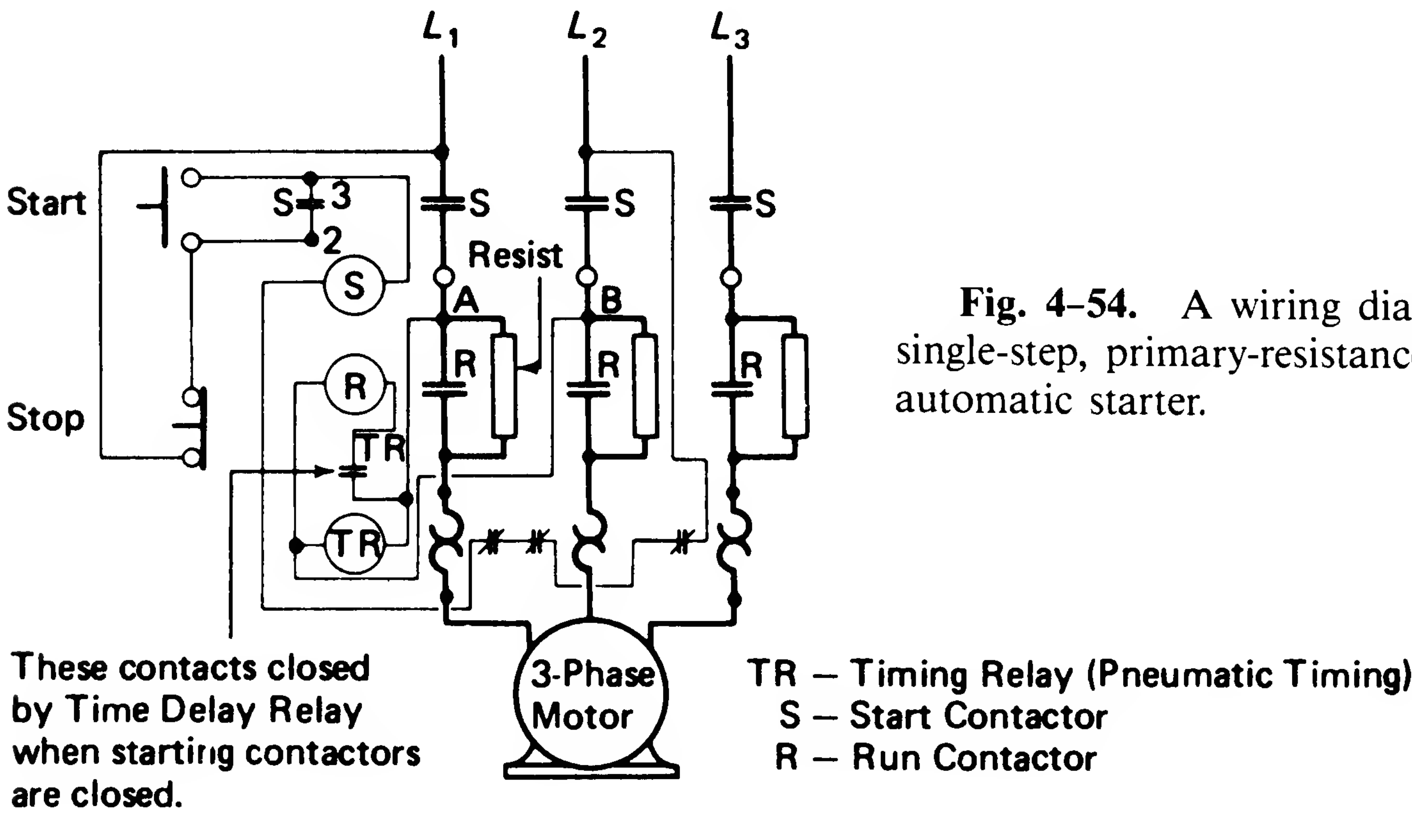


Fig. 4–54. A wiring diagram of a single-step, primary-resistance type of automatic starter.

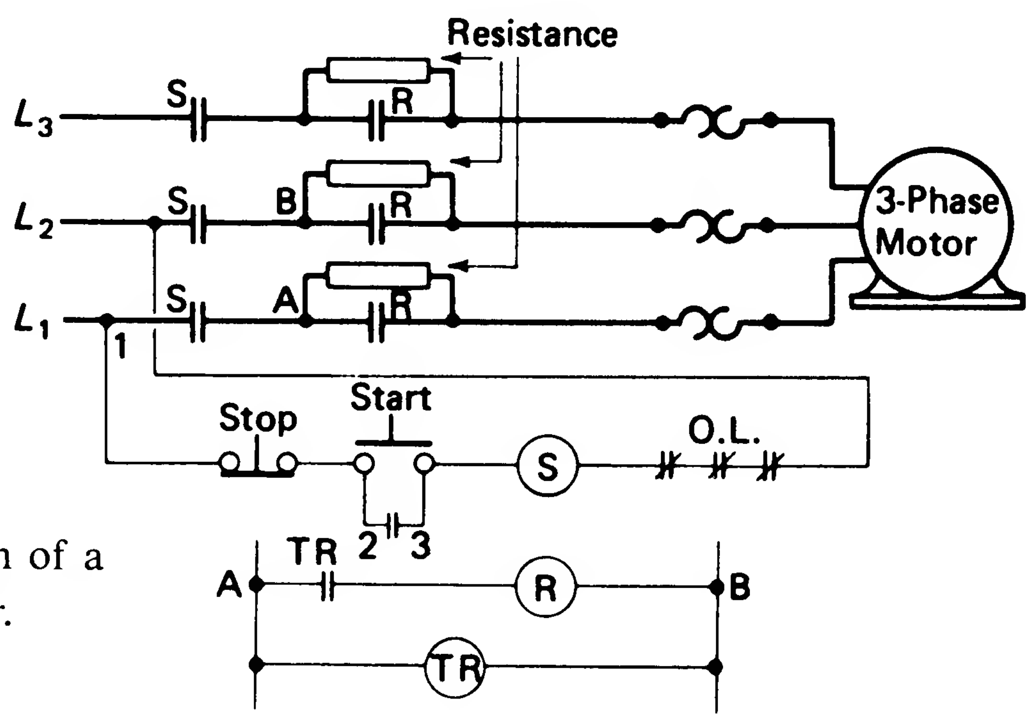


Fig. 4–55. An elementary diagram of a primary-resistance automatic starter.

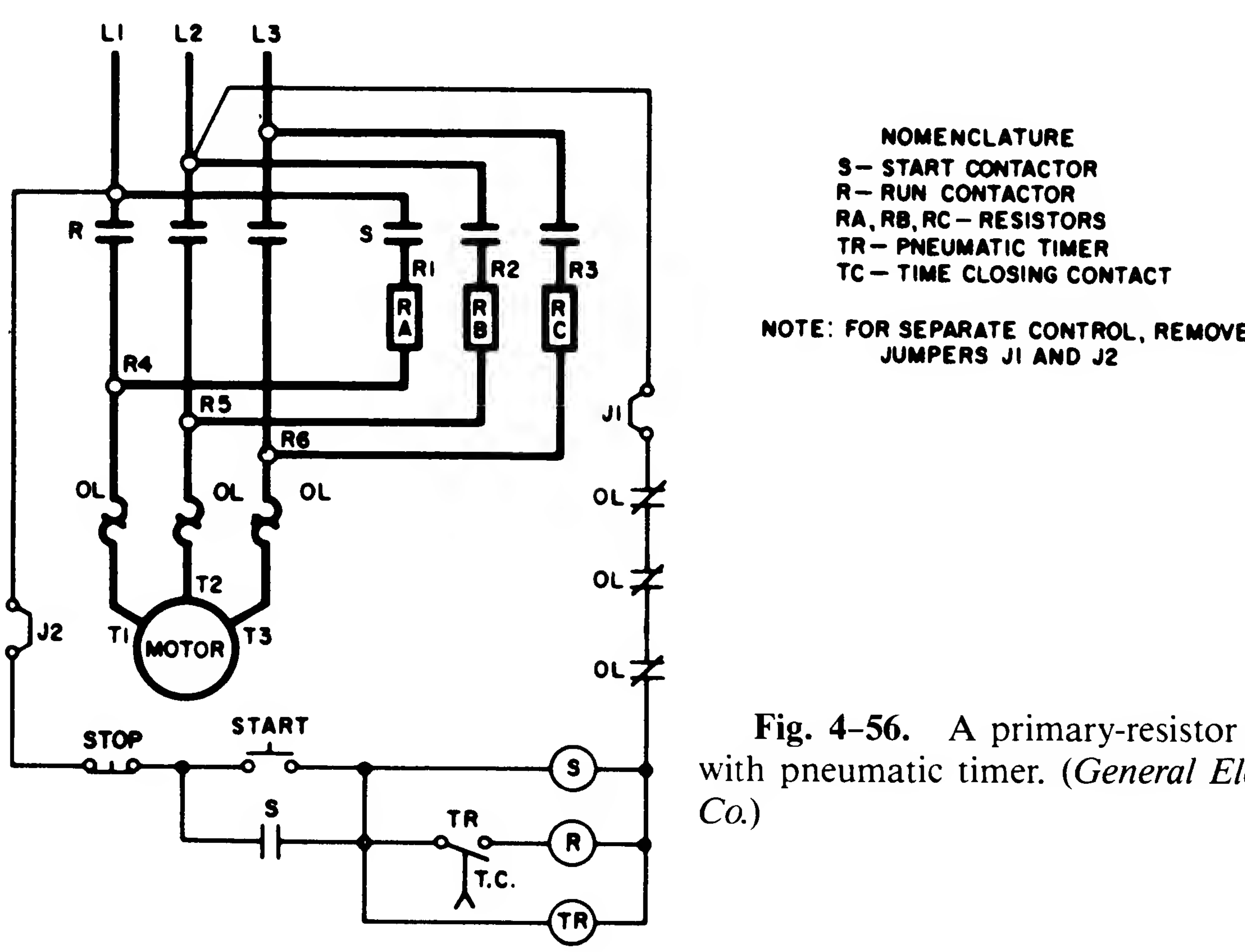


Fig. 4–56. A primary-resistor stator with pneumatic timer. (*General Electric Co.*)

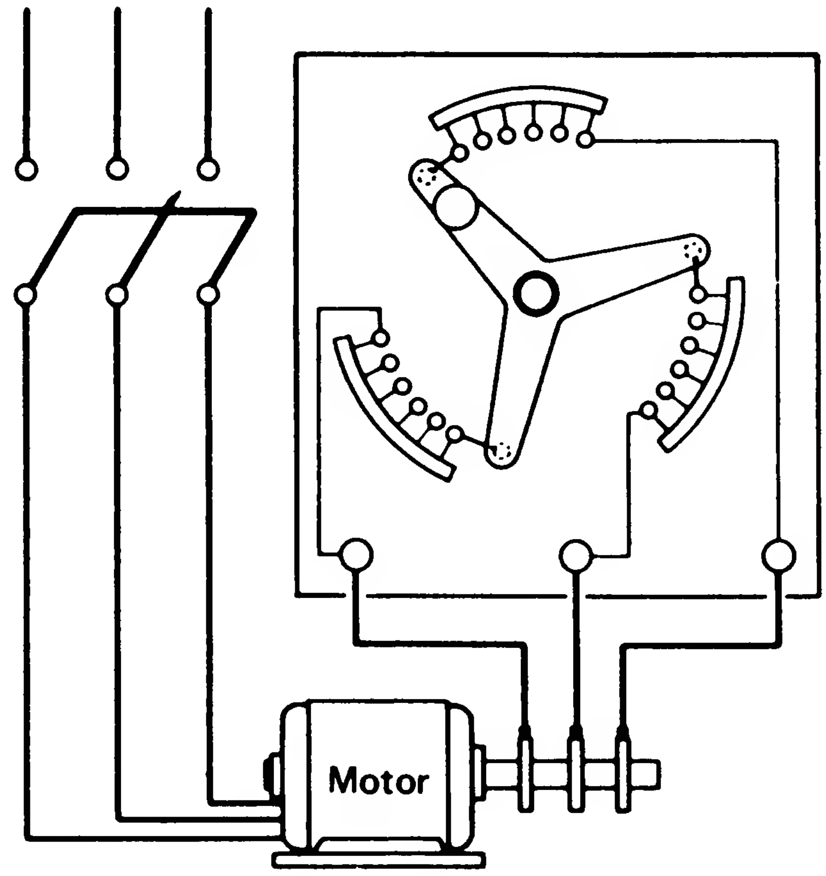


Fig. 4-57. A secondary-resistance starter connected to a wound rotor. A three-pole manual switch is used for the stator.

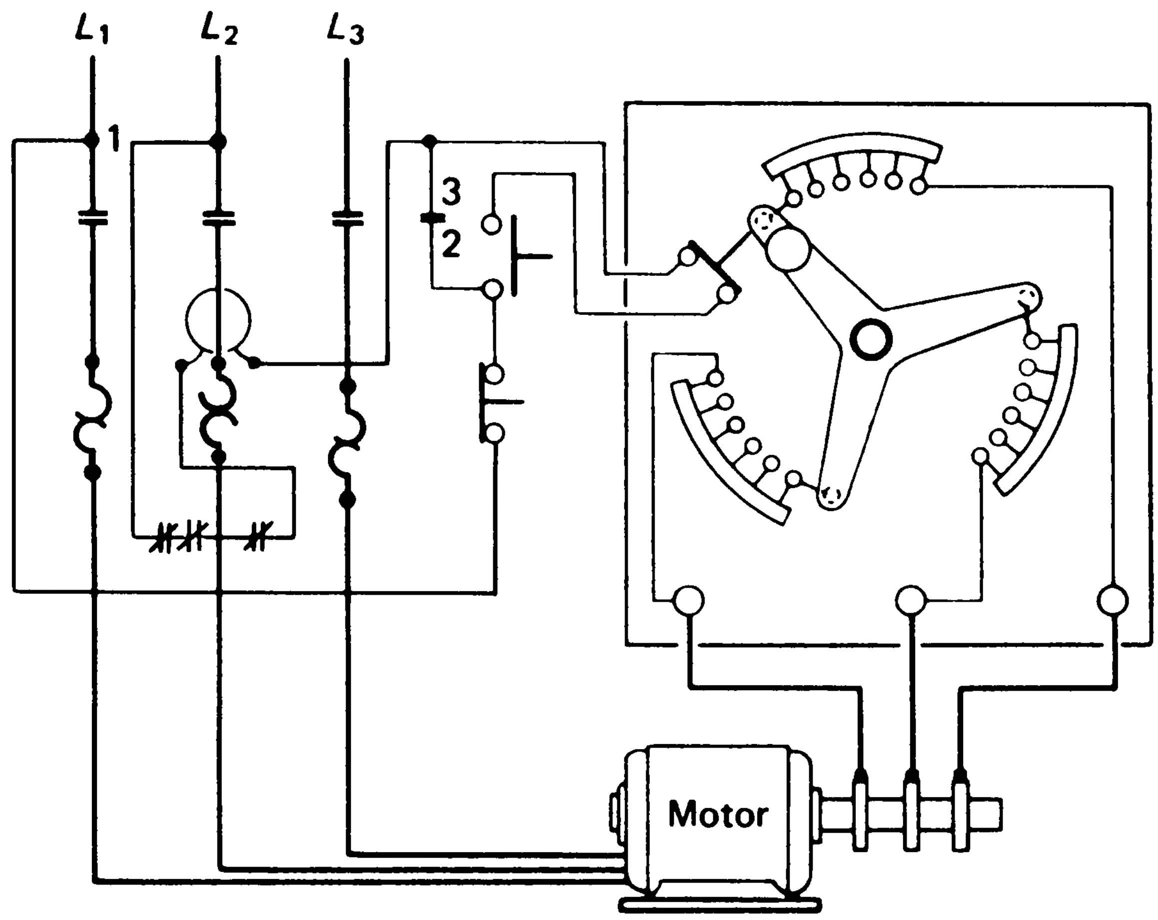


Fig. 4-58. A resistance starter connected to a magnetic switch.

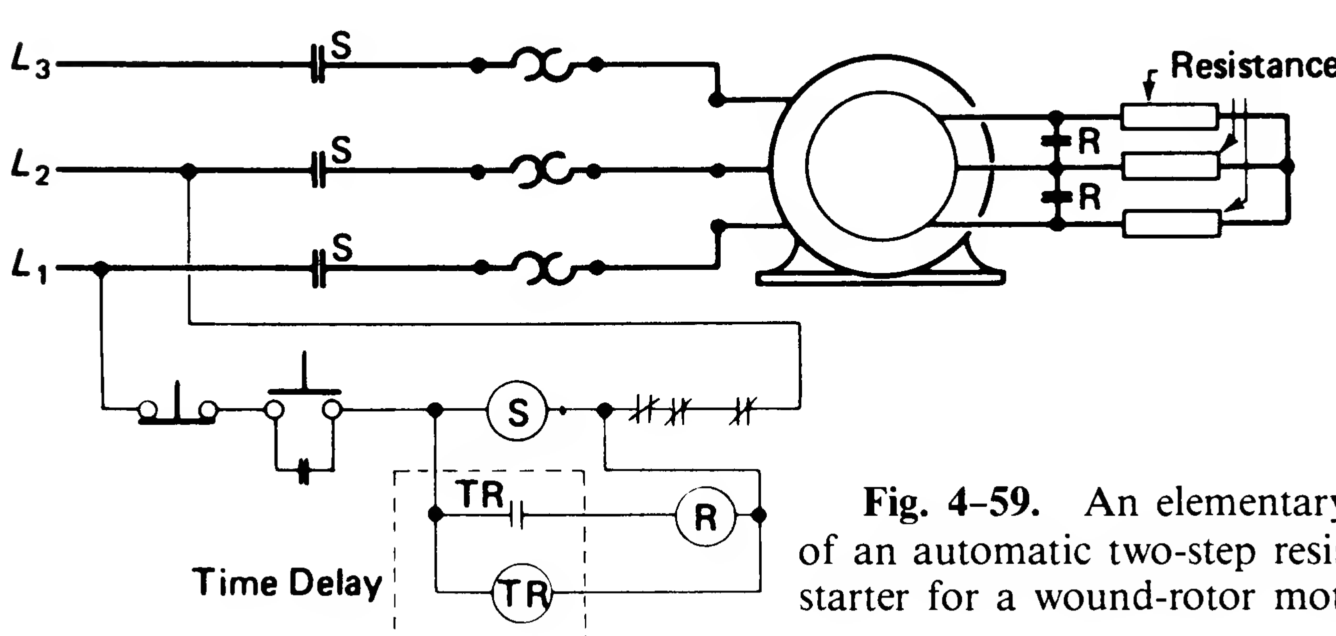


Fig. 4-59. An elementary diagram of an automatic two-step resistance starter for a wound-rotor motor.

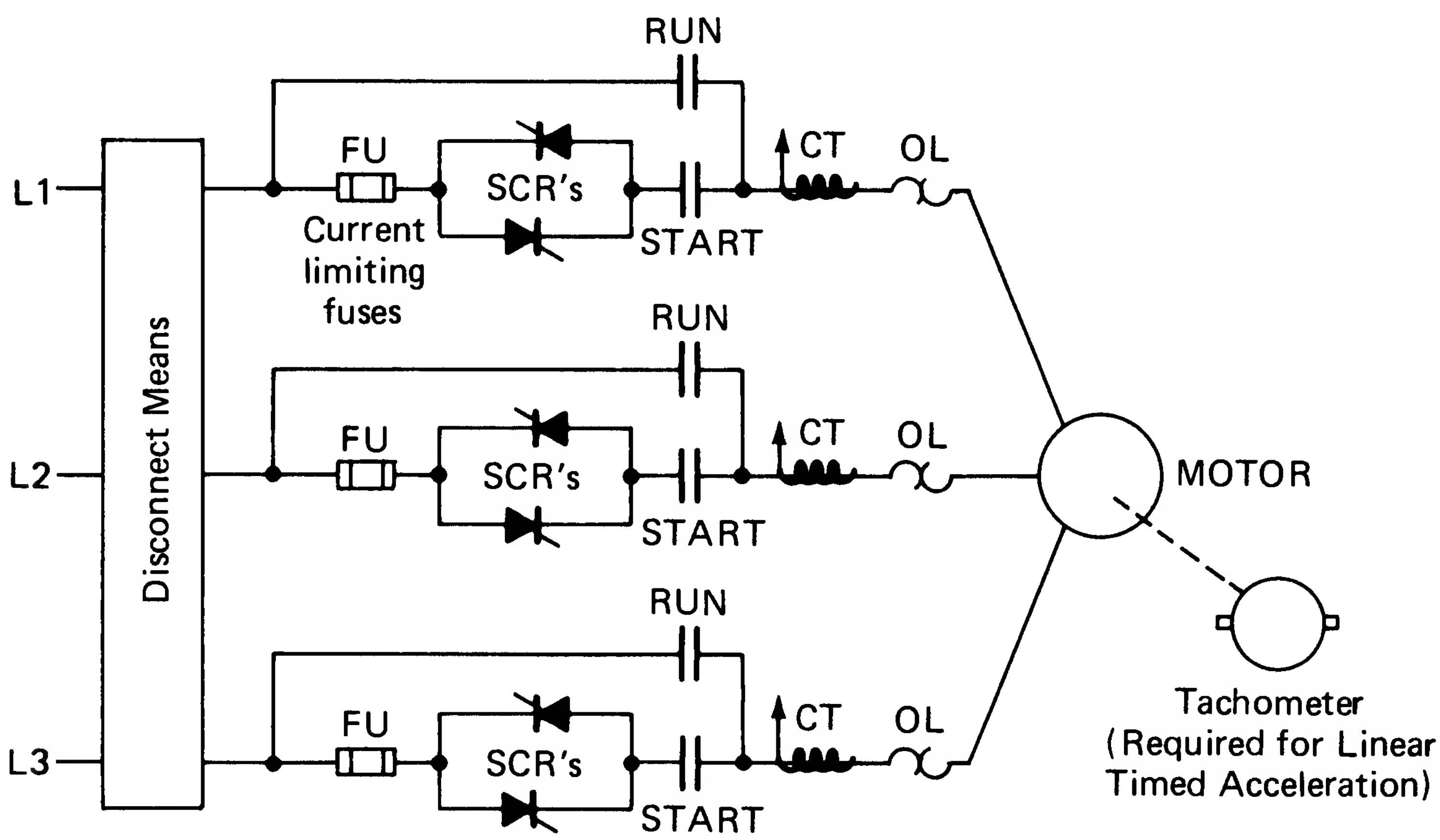


Fig. 4-60. The simplified wiring diagram of a solid-state, reduced-voltage starter. (*Allen-Bradley Co.*)

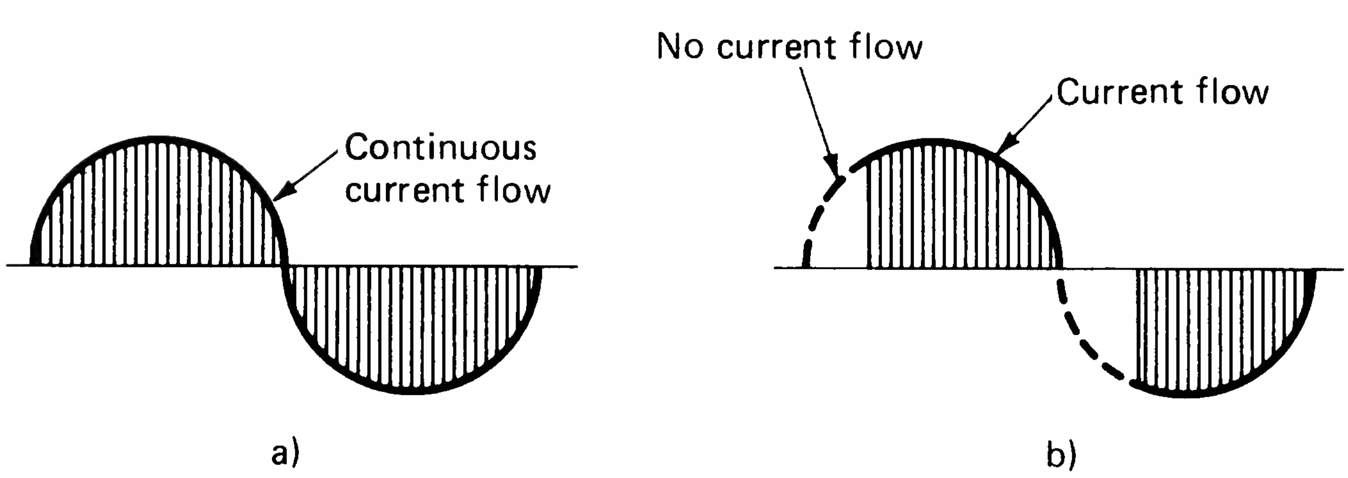


Fig. 4-61. A comparison with the normal sine wave (a) and the sine wave of the reduced-voltage part of the starting cycle (b).

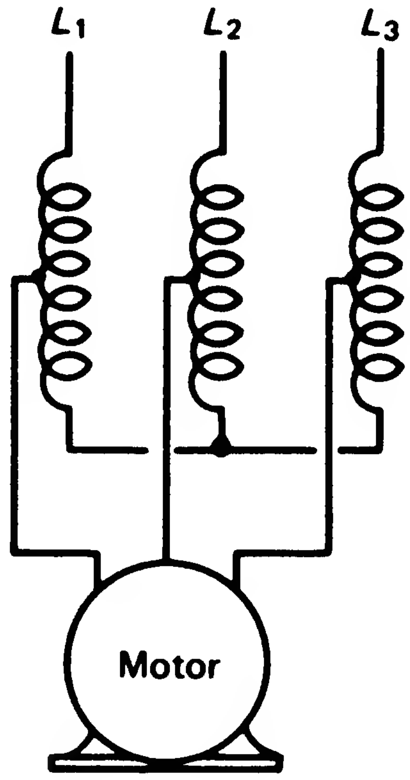


Fig. 4-62. The connection of a start position of a compensator.

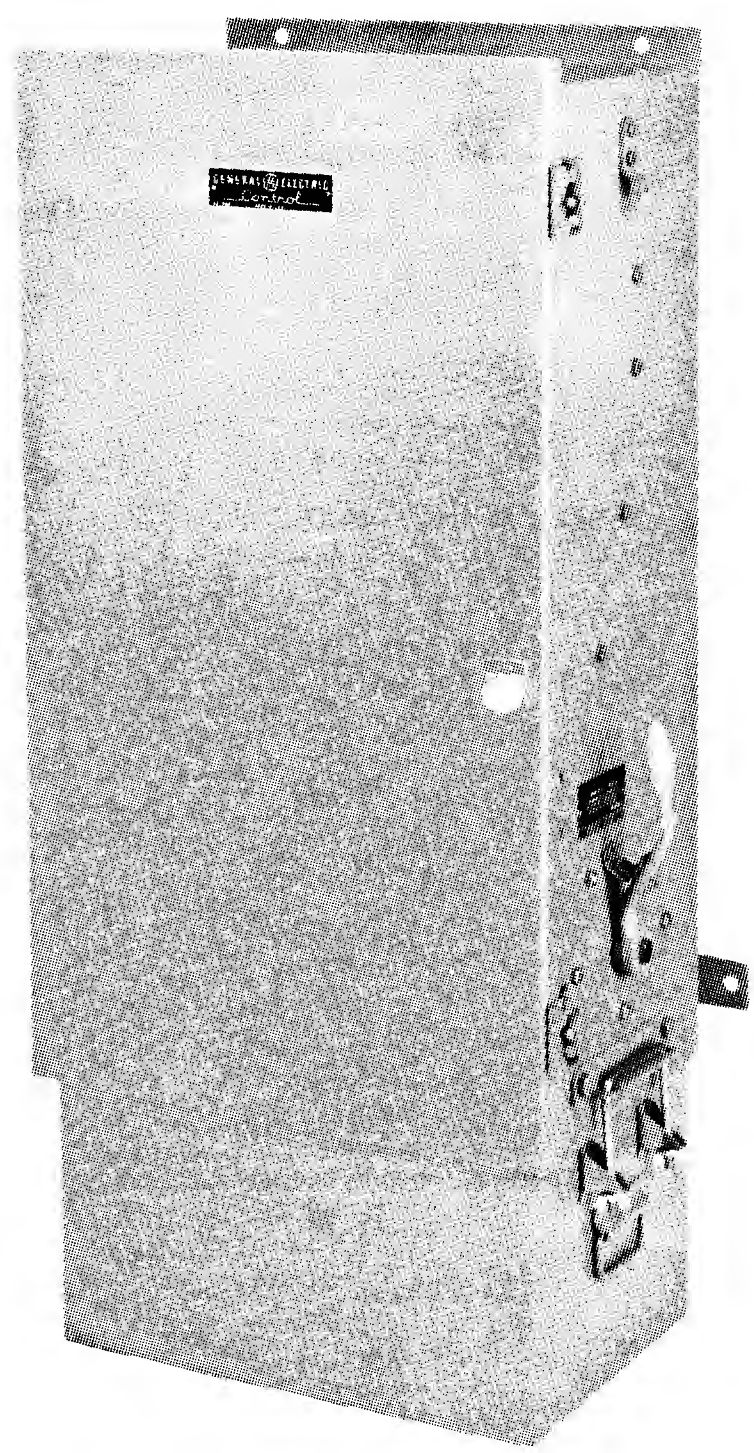


Fig. 4-63. Autotransformer type manual starter. (*General Electric Co.*)

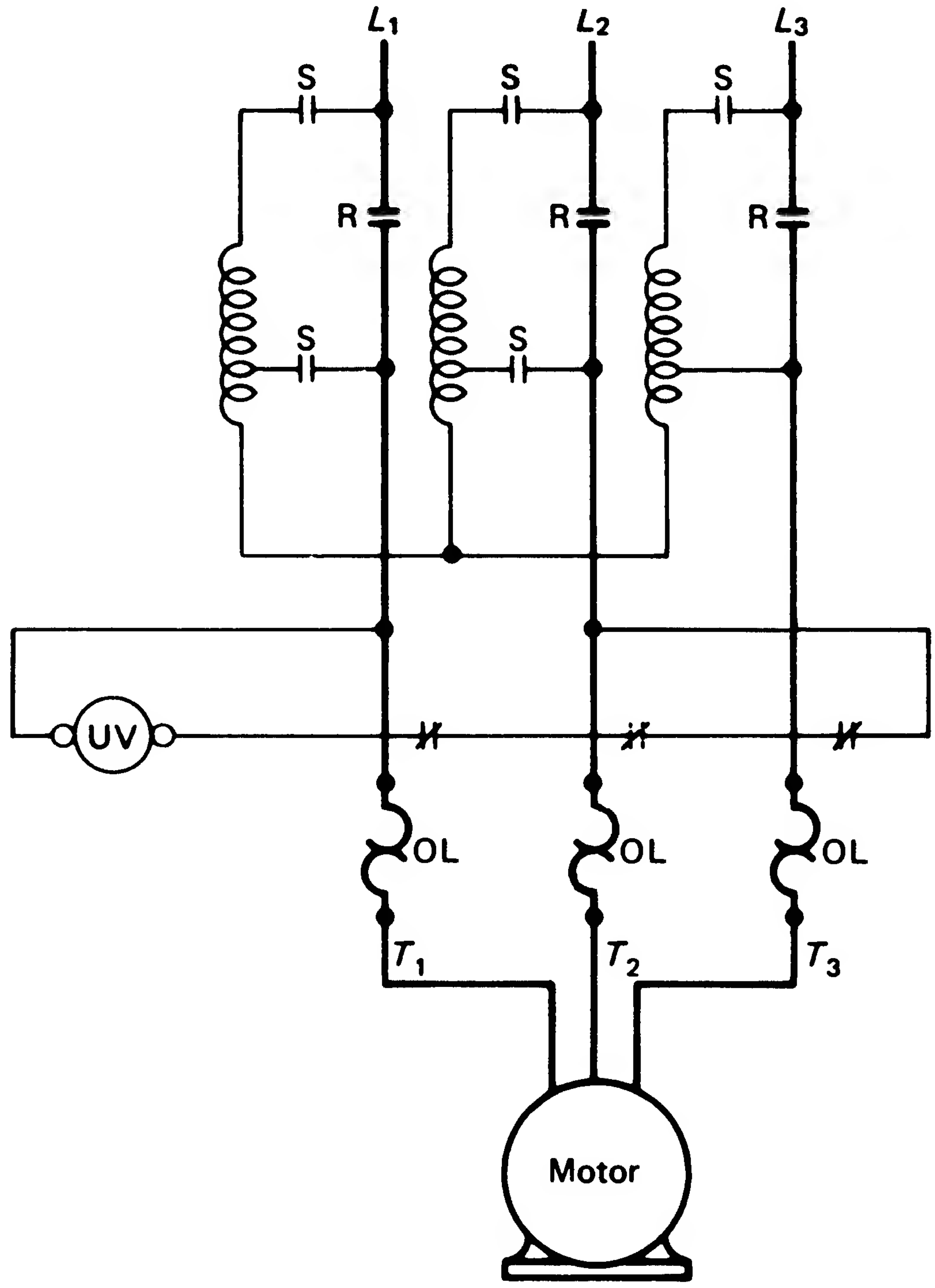


Fig. 4-64. Schematic diagram of a manually operated three-phase autotransformer starter.

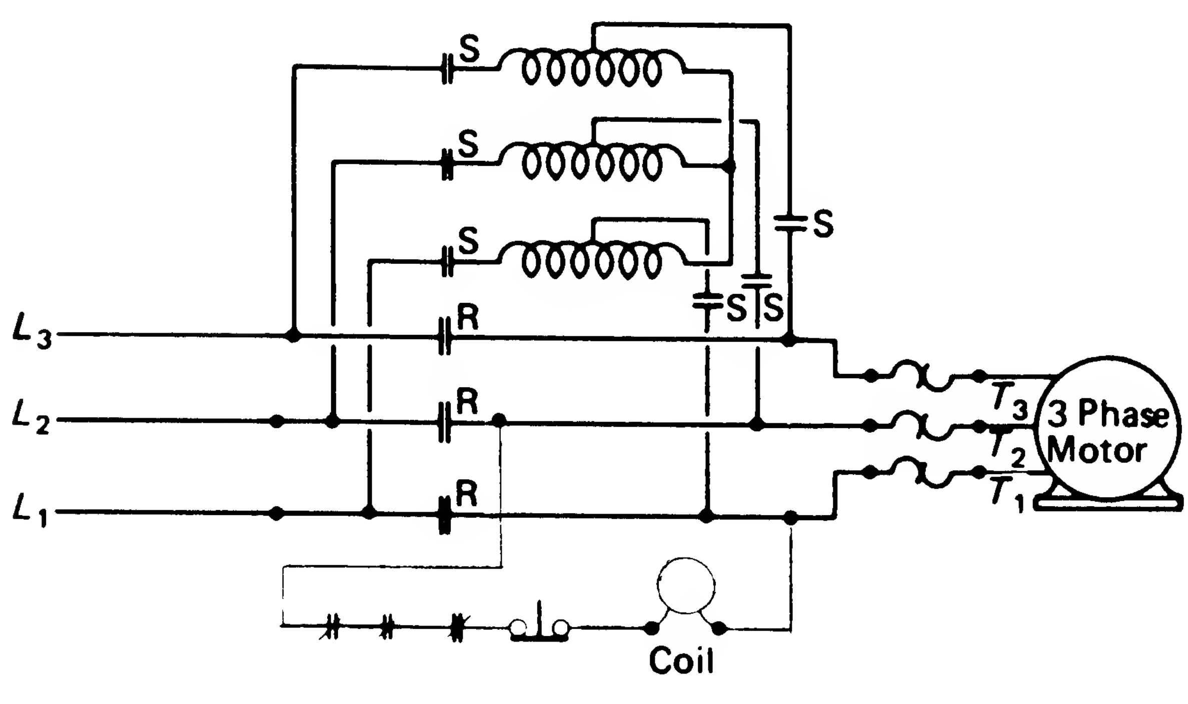


Fig. 4-65. An elementary diagram of a three-phase compensator.

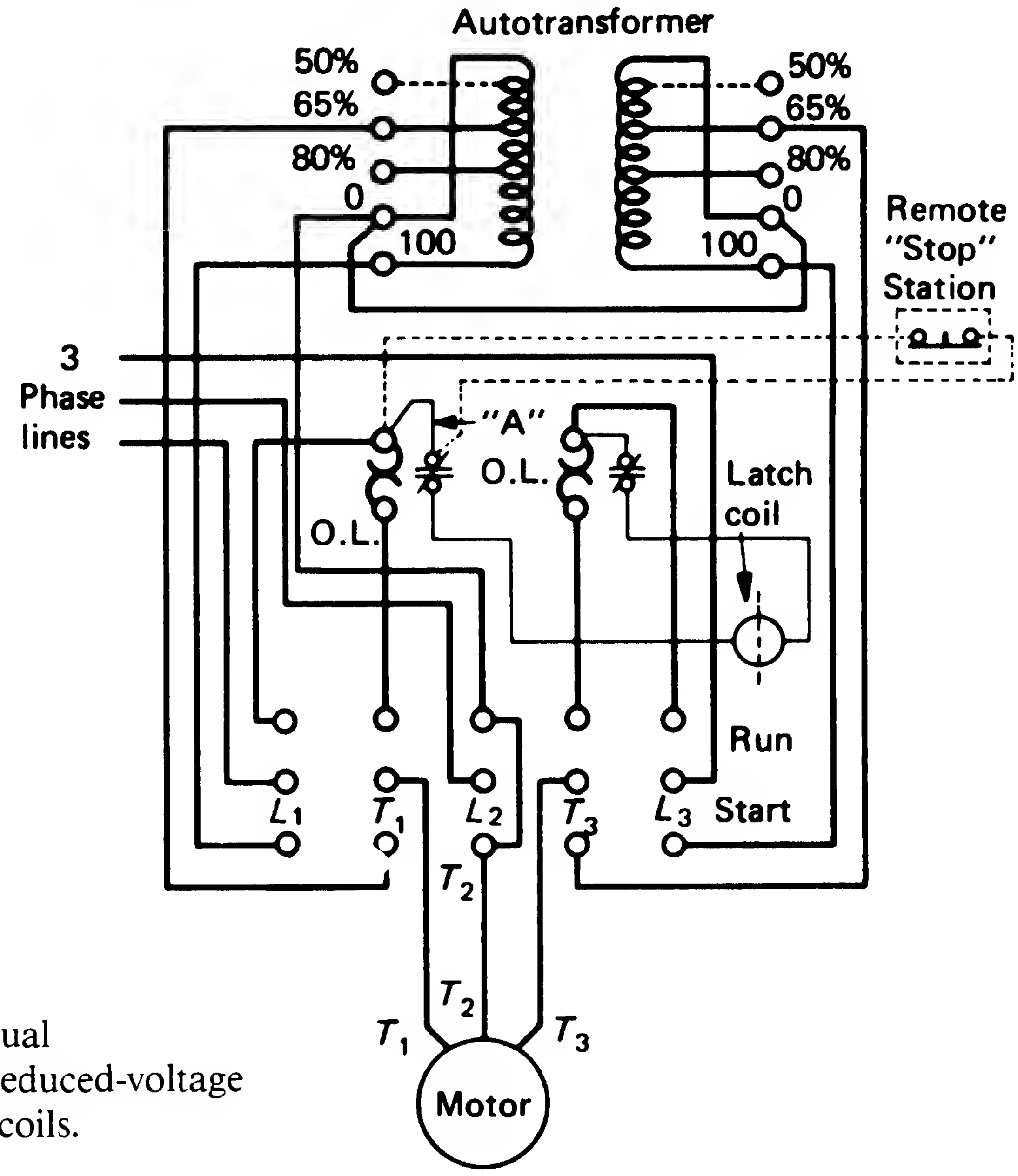


Fig. 4-66. A manual autotransformer type reduced-voltage starter using two A.T. coils.

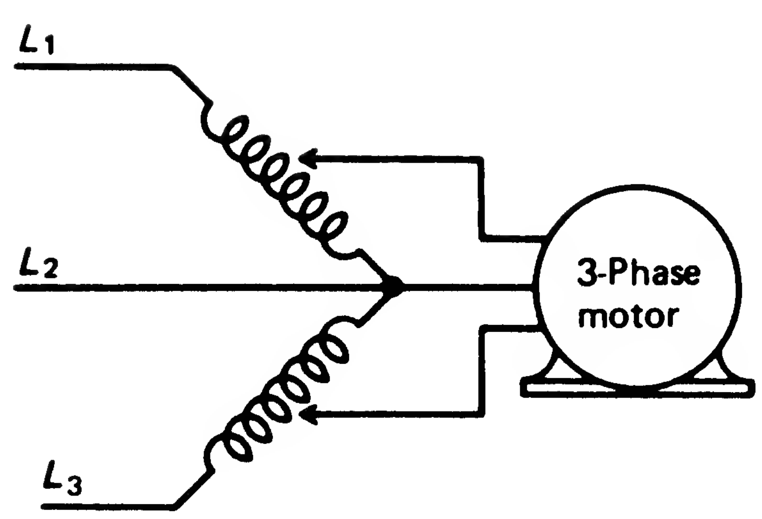


Fig. 4-67. A line diagram of a two-coil, three-phase compensator on START position. Note the open-delta connection.

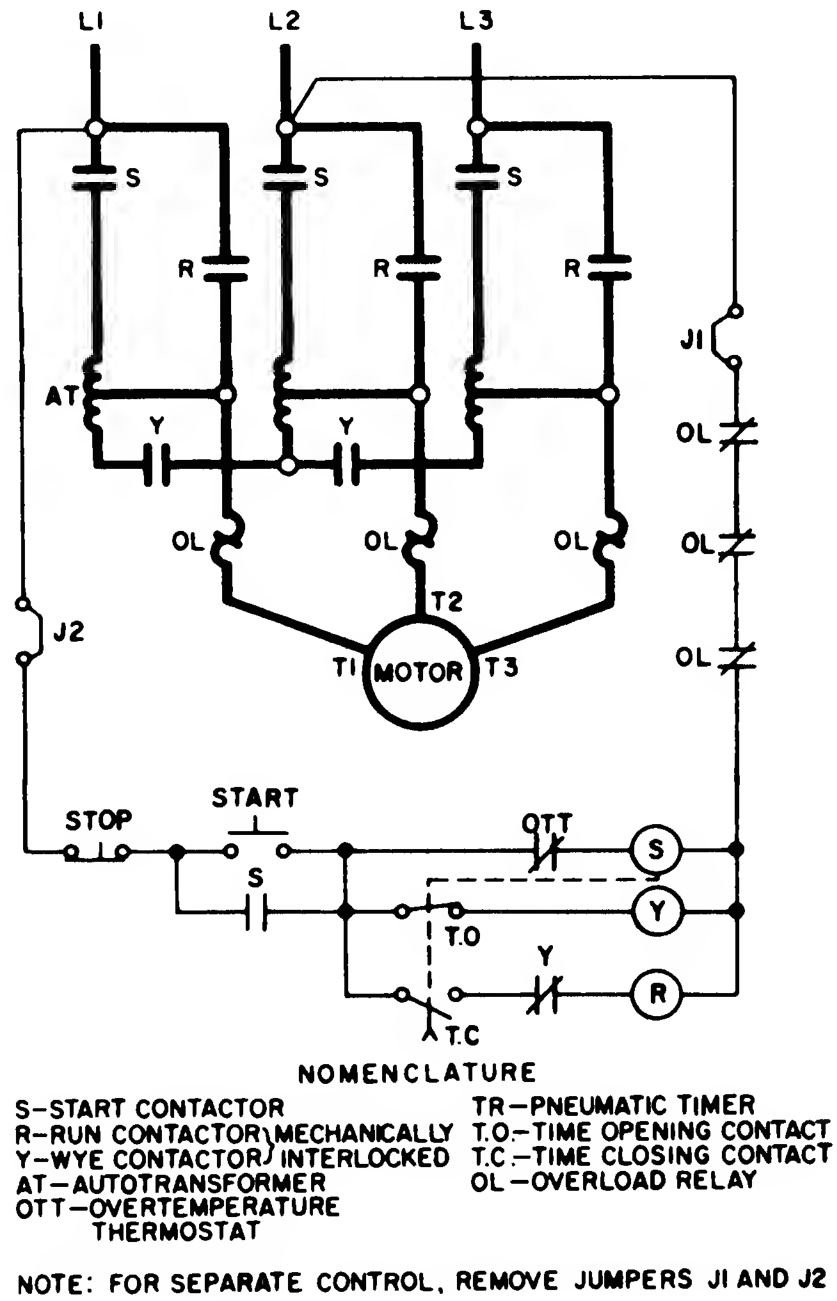


Fig. 4-68. Motor and control circuit of an autotransformer type magnetic starter. (*General Electric Co.*)

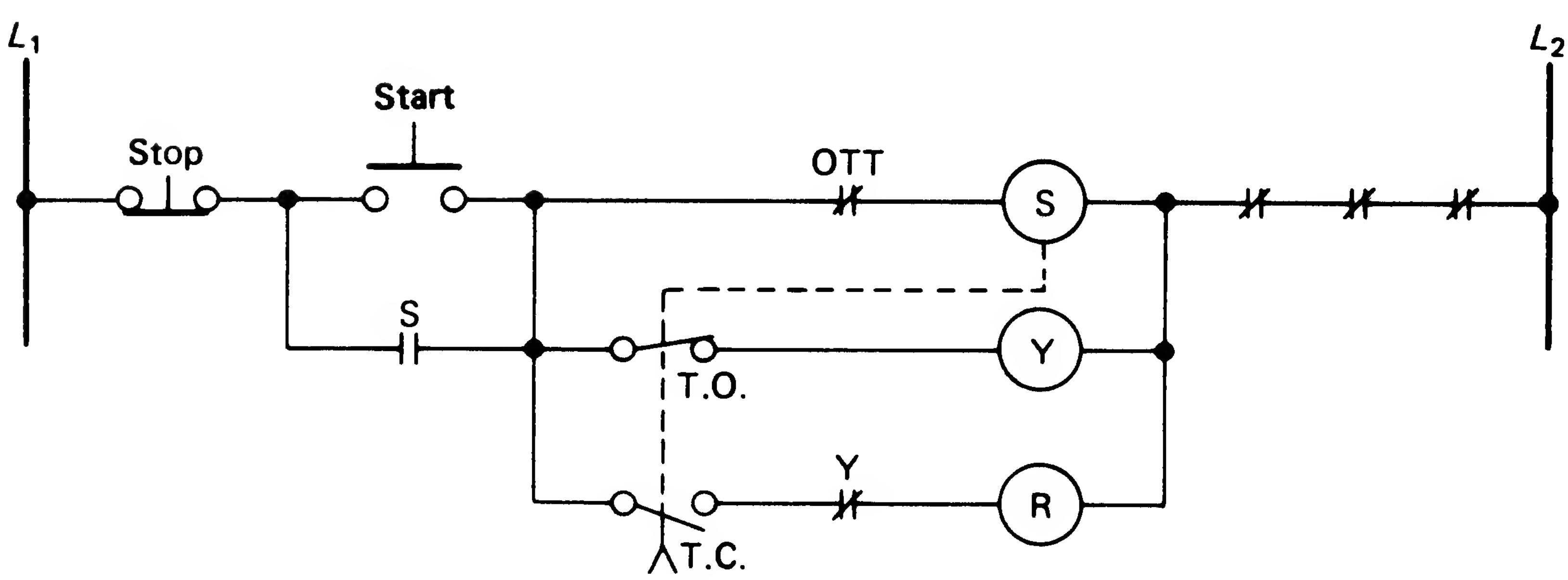


Fig. 4-69. Control circuits of **Fig. 4-68**.

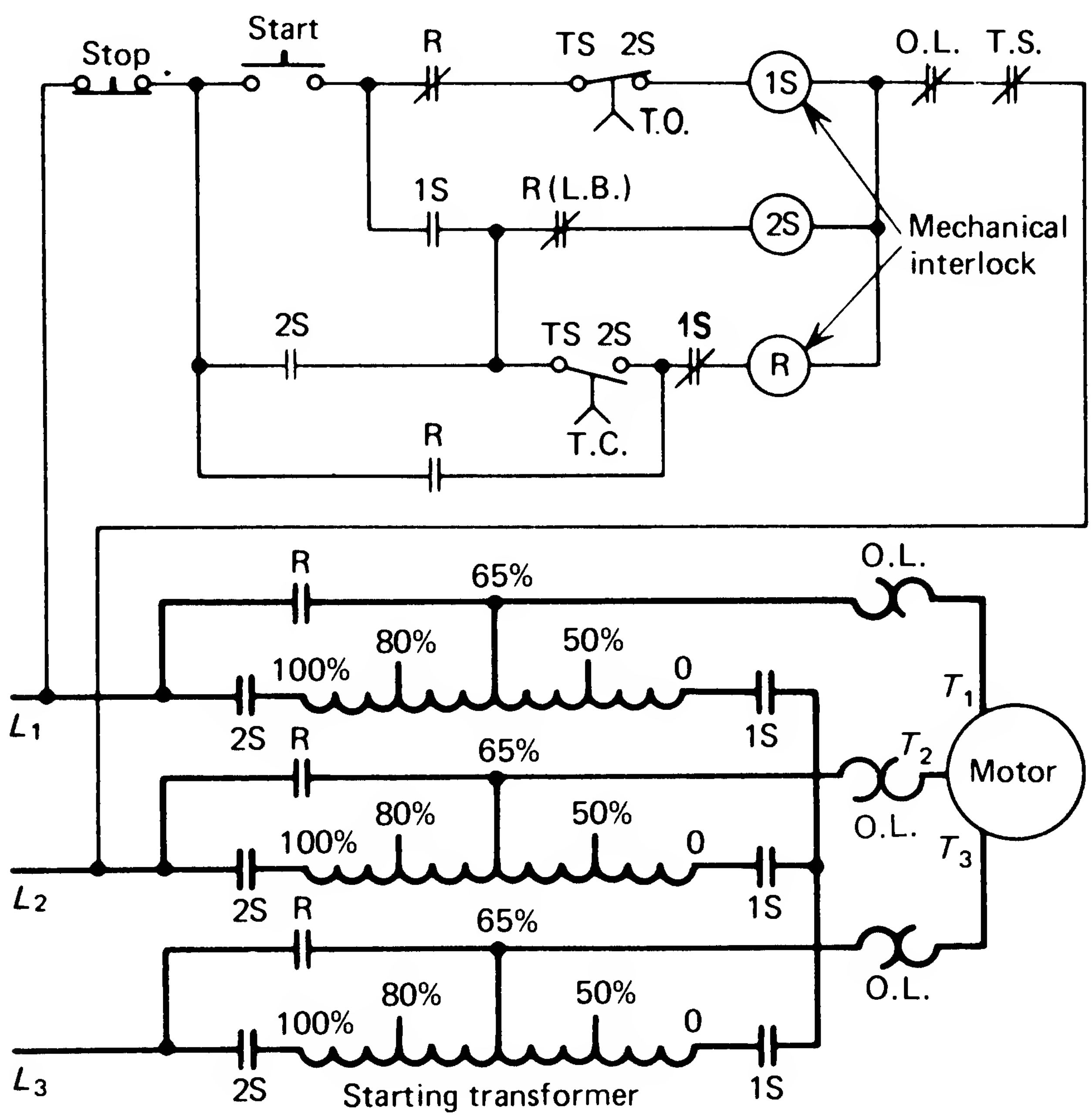
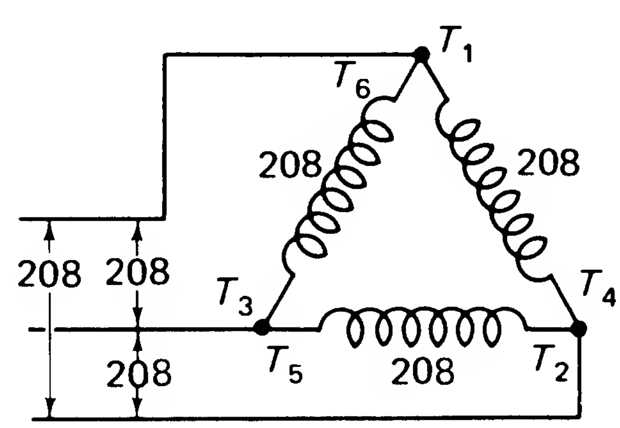
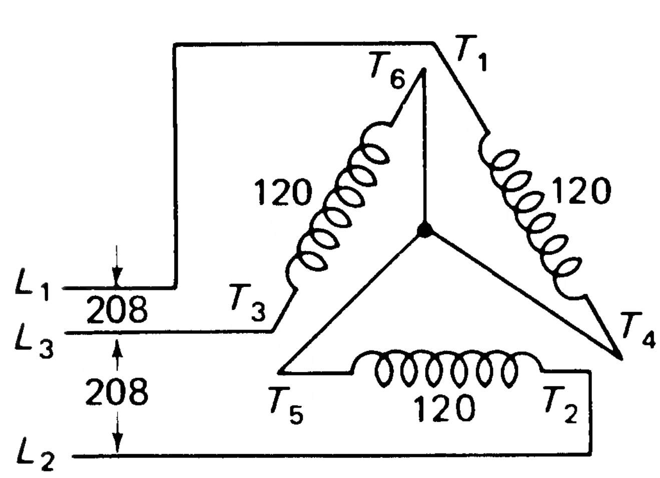


Fig. 4-70. Autotransformer type reduced-voltage magnetic starter.

Fig. 4-71. Each phase of a delta-connected motor receives the full line voltage.





	L_1	L_2	L_3	Together
Start	T_1	T_2	T_3	$(T_4\ T_5\ T_6)$
Run	T_1T_6	T_2T_4	T_3T_5	———————

Fig. 4-72. If a delta-connected motor is connected wye, each phase will receive 58 percent of line voltage.

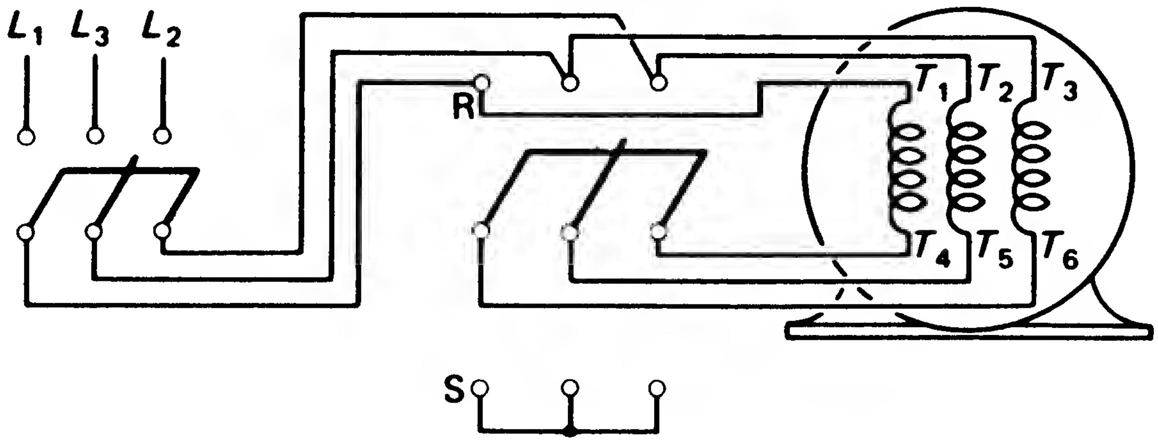


Fig. 4–73. A star-delta connection for reduced-voltage starting.

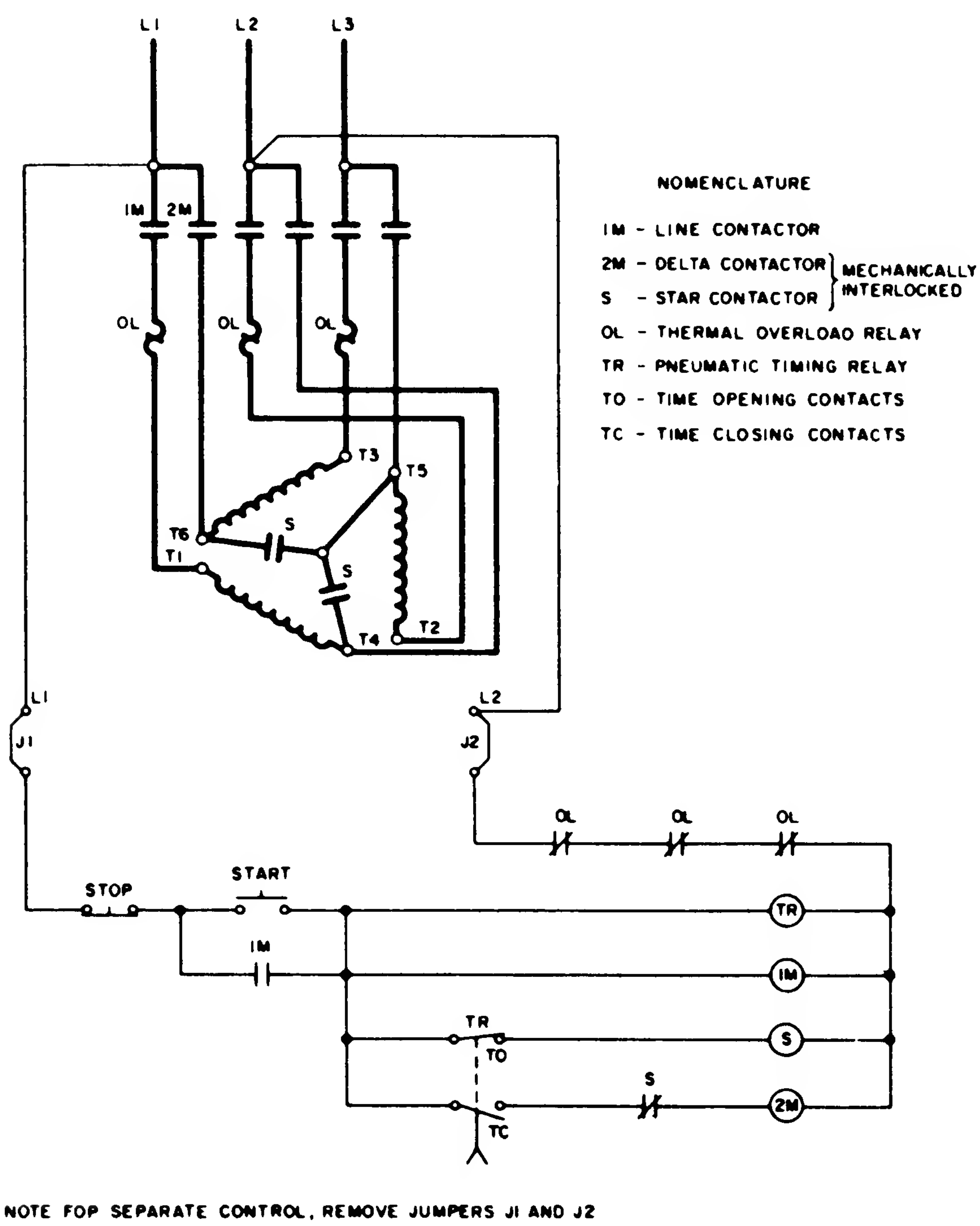


Fig. 4–74. Wye delta starter of the open transition type. *(General Electric Co.)*

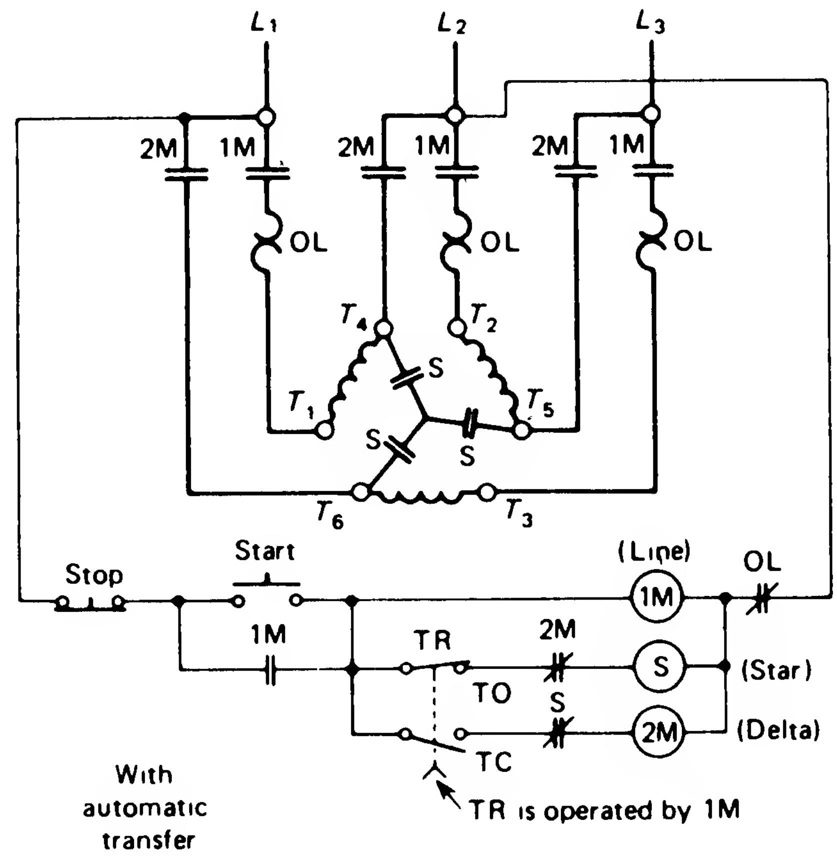


Fig. 4-75. Wye-delta magnetic starter. (*General Electric Co.*)

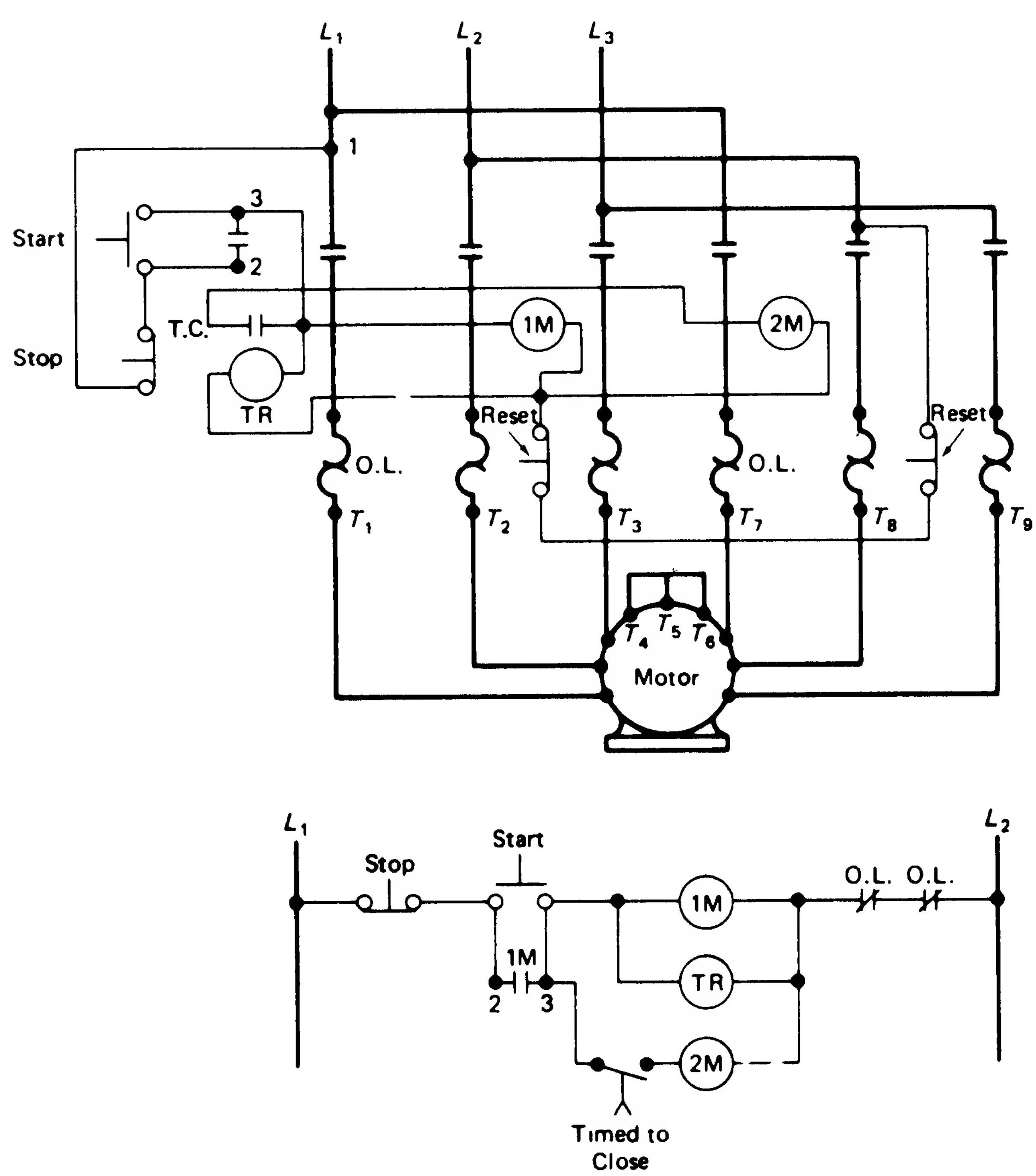


Fig. 4-76. Part-winding magnetic starter for wye-connected motor.

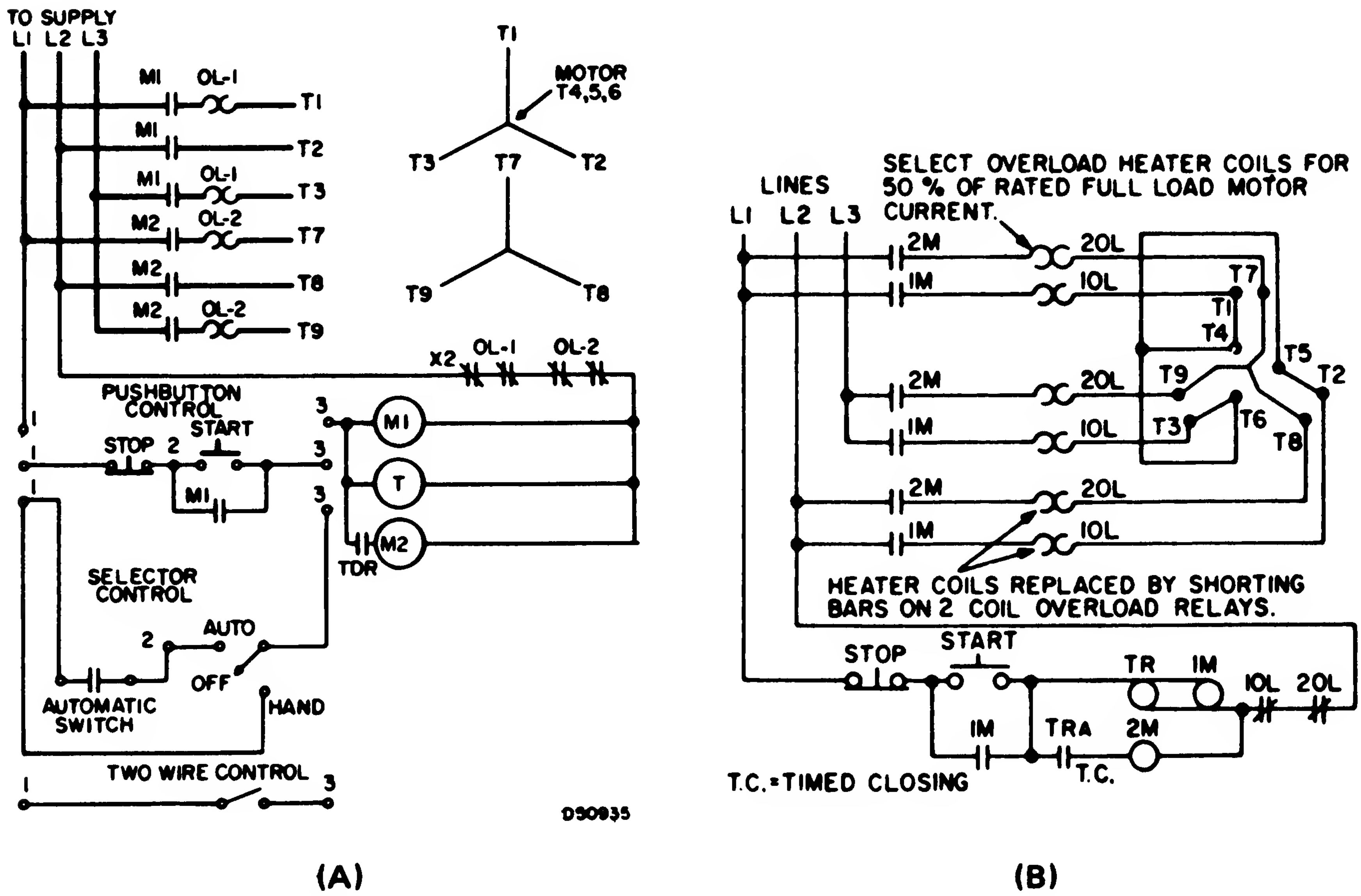
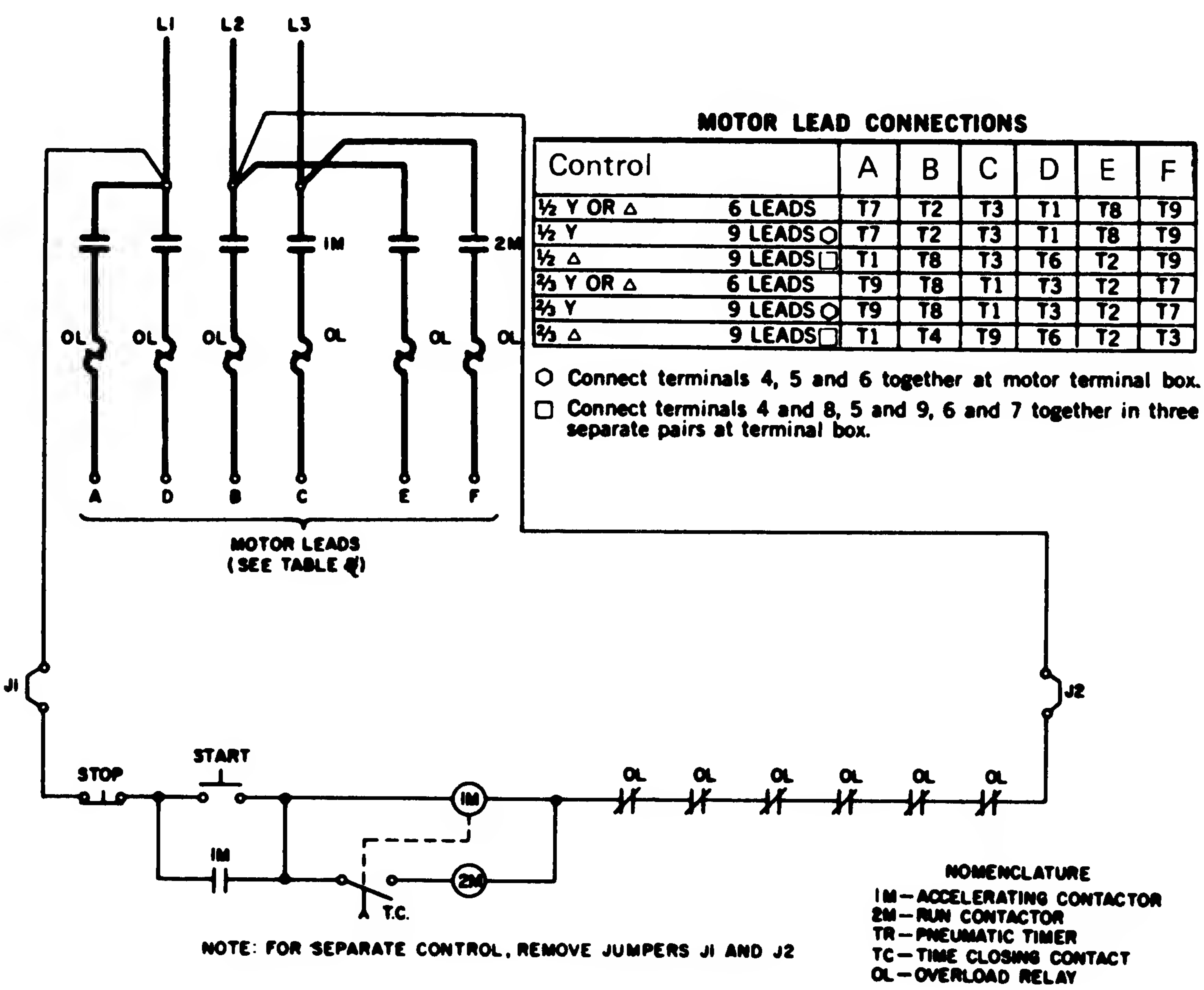


Fig. 4–77. Typical wiring diagrams of two step increment starting. A: (*Furness Electric*) B: (*Cutler Hammer*)



MOTOR LEAD CONNECTIONS

Control		A	B	C	D	E	F
½ Y OR Δ	6 LEADS	T7	T2	T3	T1	T8	T9
½ Y	9 LEADS ○	T7	T2	T3	T1	T8	T9
½ Δ	9 LEADS □	T1	T8	T3	T6	T2	T9
⅔ Y OR Δ	6 LEADS	T9	T8	T1	T3	T2	T7
⅔ Y	9 LEADS ○	T9	T8	T1	T3	T2	T7
⅔ Δ	9 LEADS □	T1	T4	T9	T6	T2	T3

○ Connect terminals 4, 5 and 6 together at motor terminal box.

□ Connect terminals 4 and 8, 5 and 9, 6 and 7 together in three separate pairs at terminal box.

Fig. 4–78. Connections for G.E. part-winding starters.

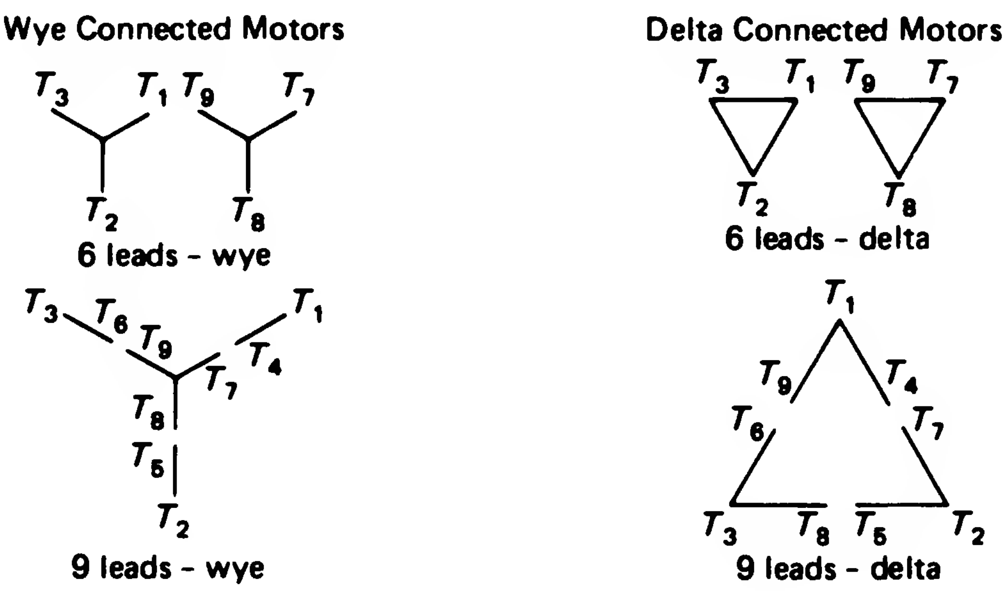


Fig. 4–78. (*continued*)

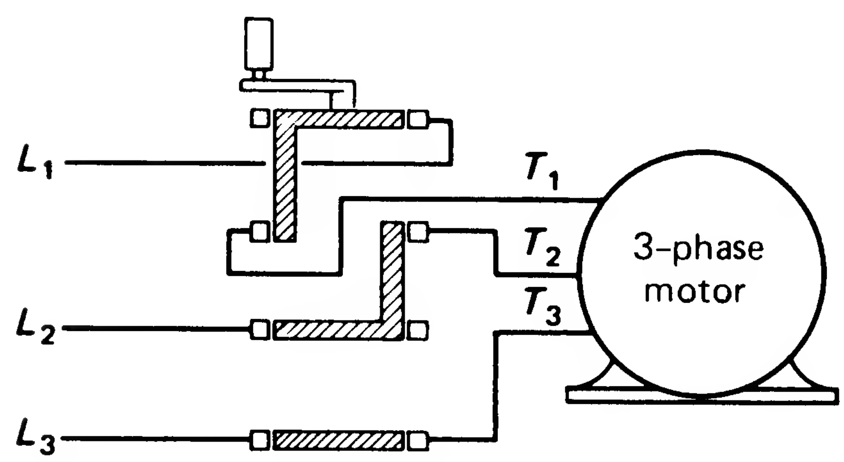


Fig. 4–79. A three-phase motor connected to a manual reversing-drum switch for clockwise rotation.

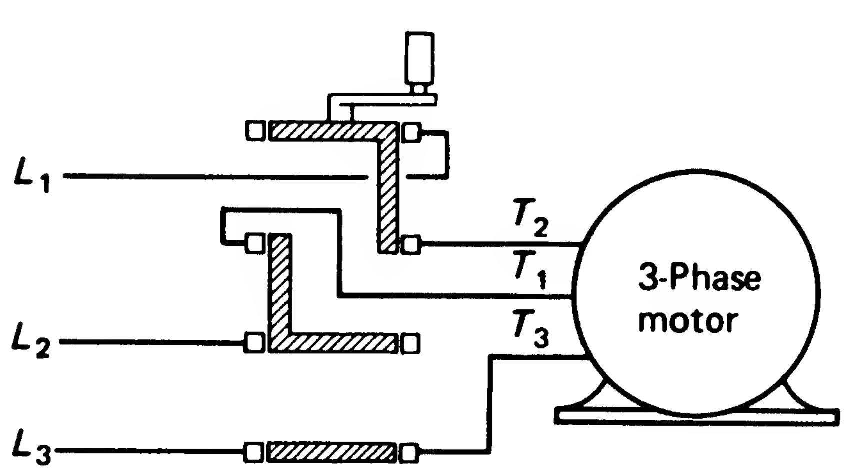


Fig. 4–80. A drum switch connected to a three-phase motor for counterclockwise rotation.

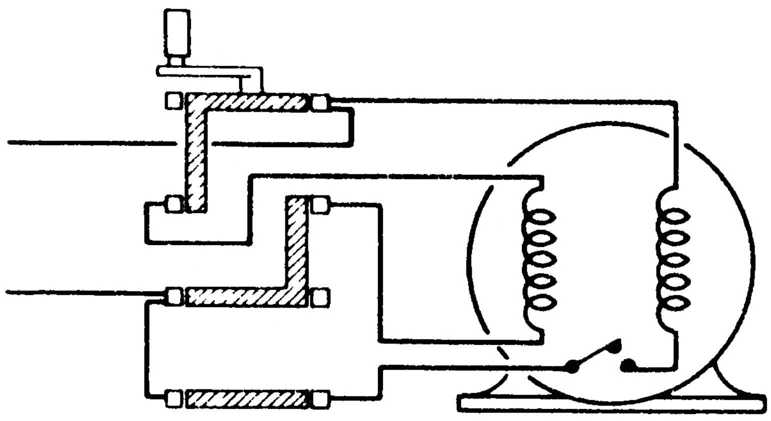


Fig. 4–81. A drum switch for reversing a split-phase motor.

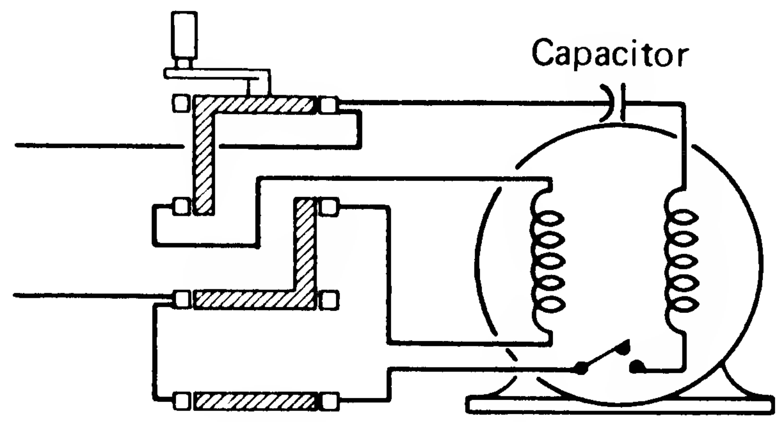


Fig. 4–82. A drum switch for reversing capacitor-start motor.

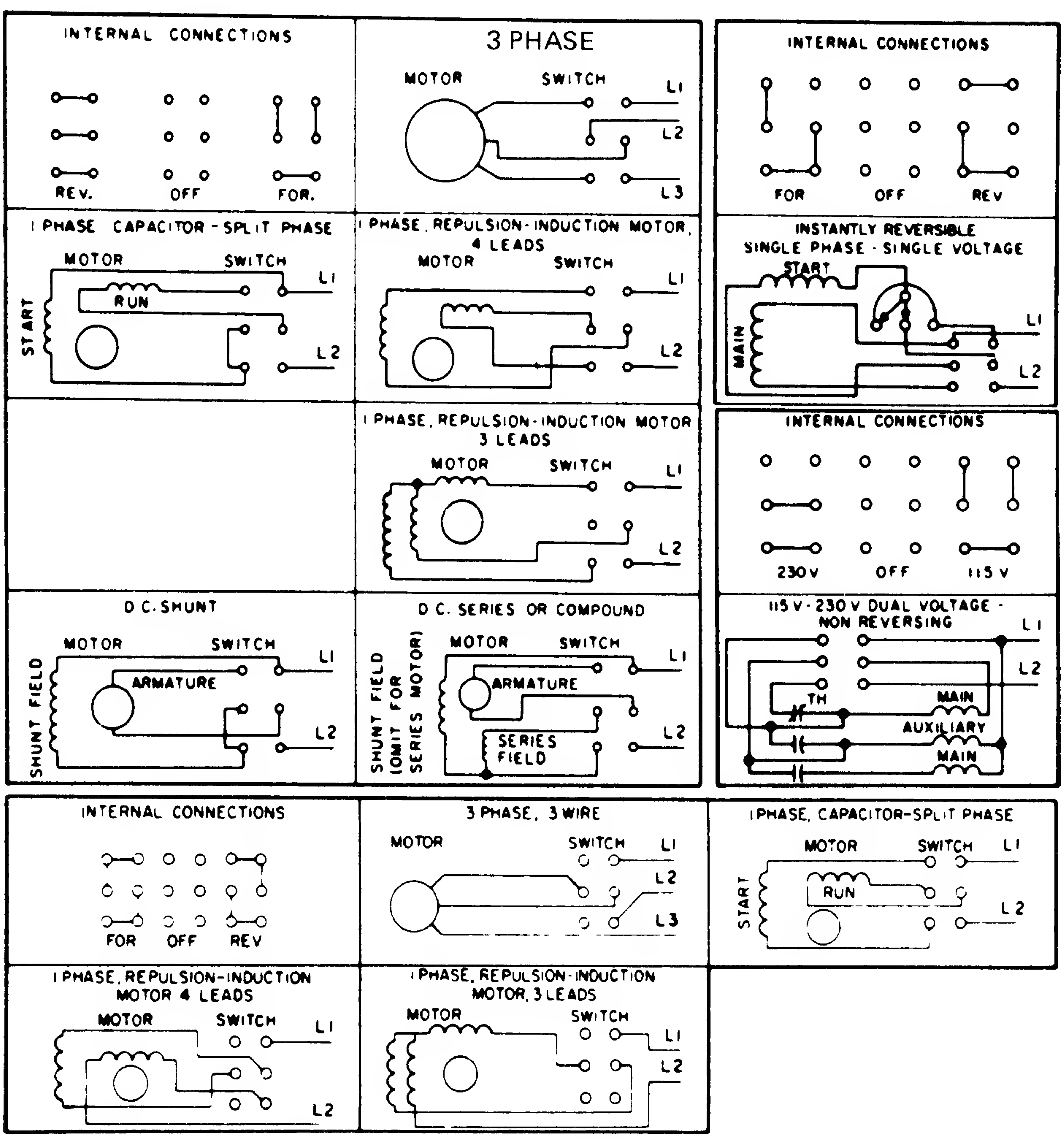
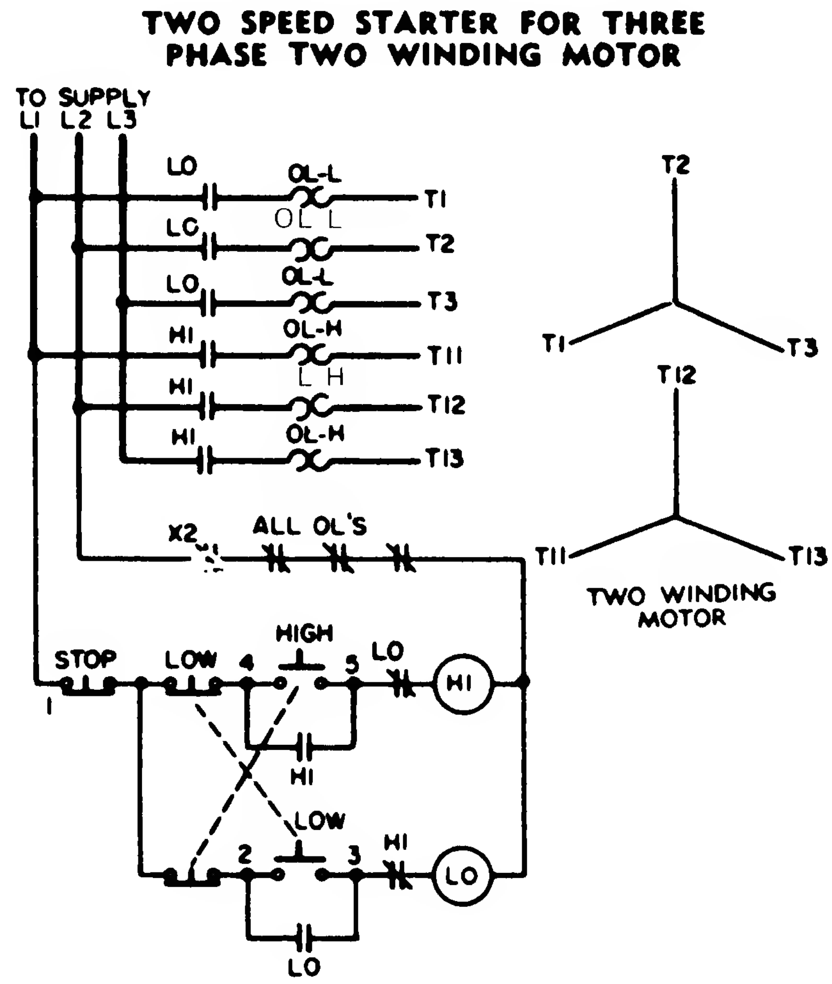


Fig. 4–83. Typical connection diagram of drum switches.



POSITION	L1	L2	L3	OPEN
LOW SPEED	T1	T2	T3	T11, T12, T13
HIGH SPEED	T11	T12	T13	T1, T2, T3

Fig. 4-84. A two-speed controller for two sets of three-phase windings.

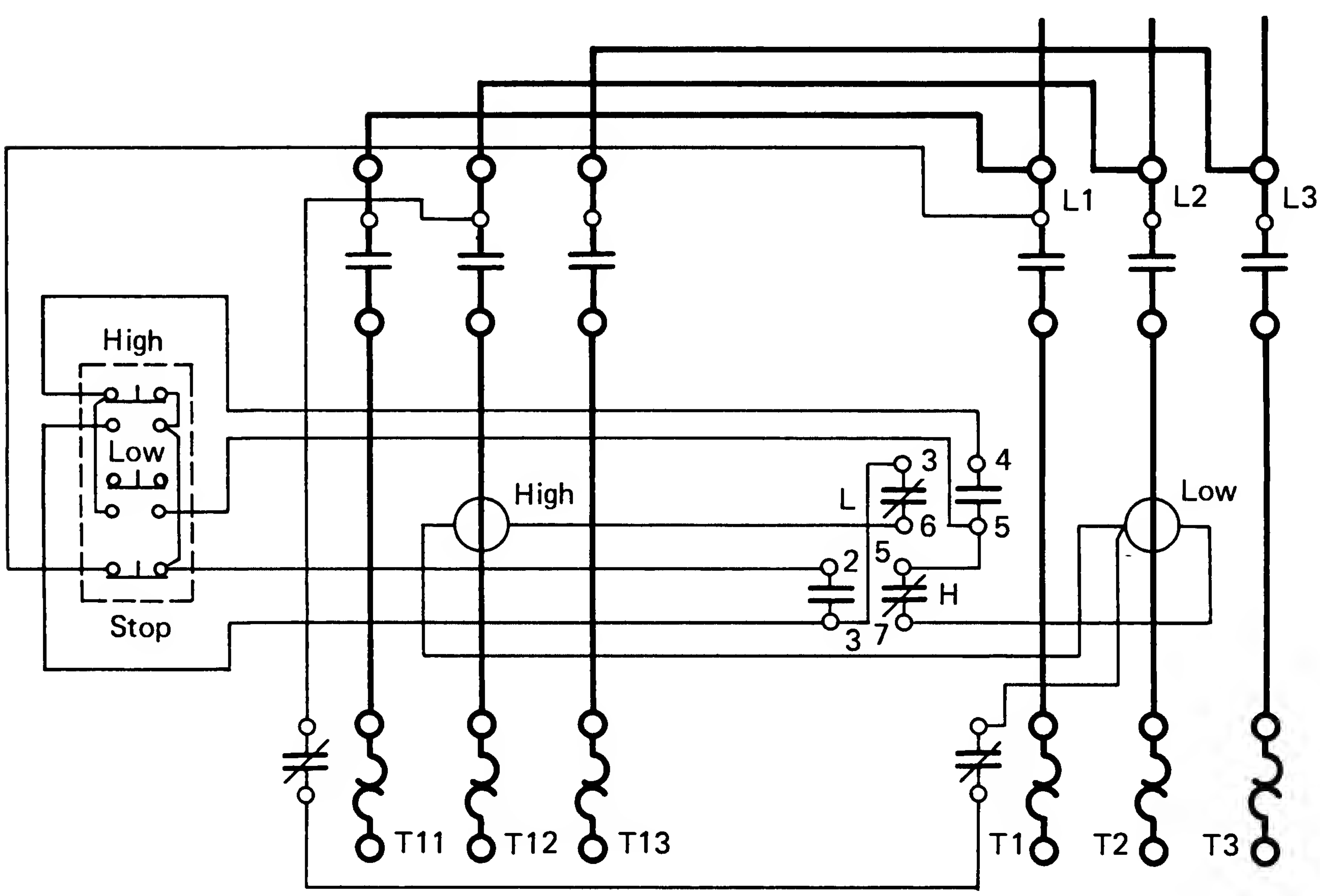


Fig. 4-85. Two-speed, two-winding full-voltage starter. (*Allen-Bradley Co.*)

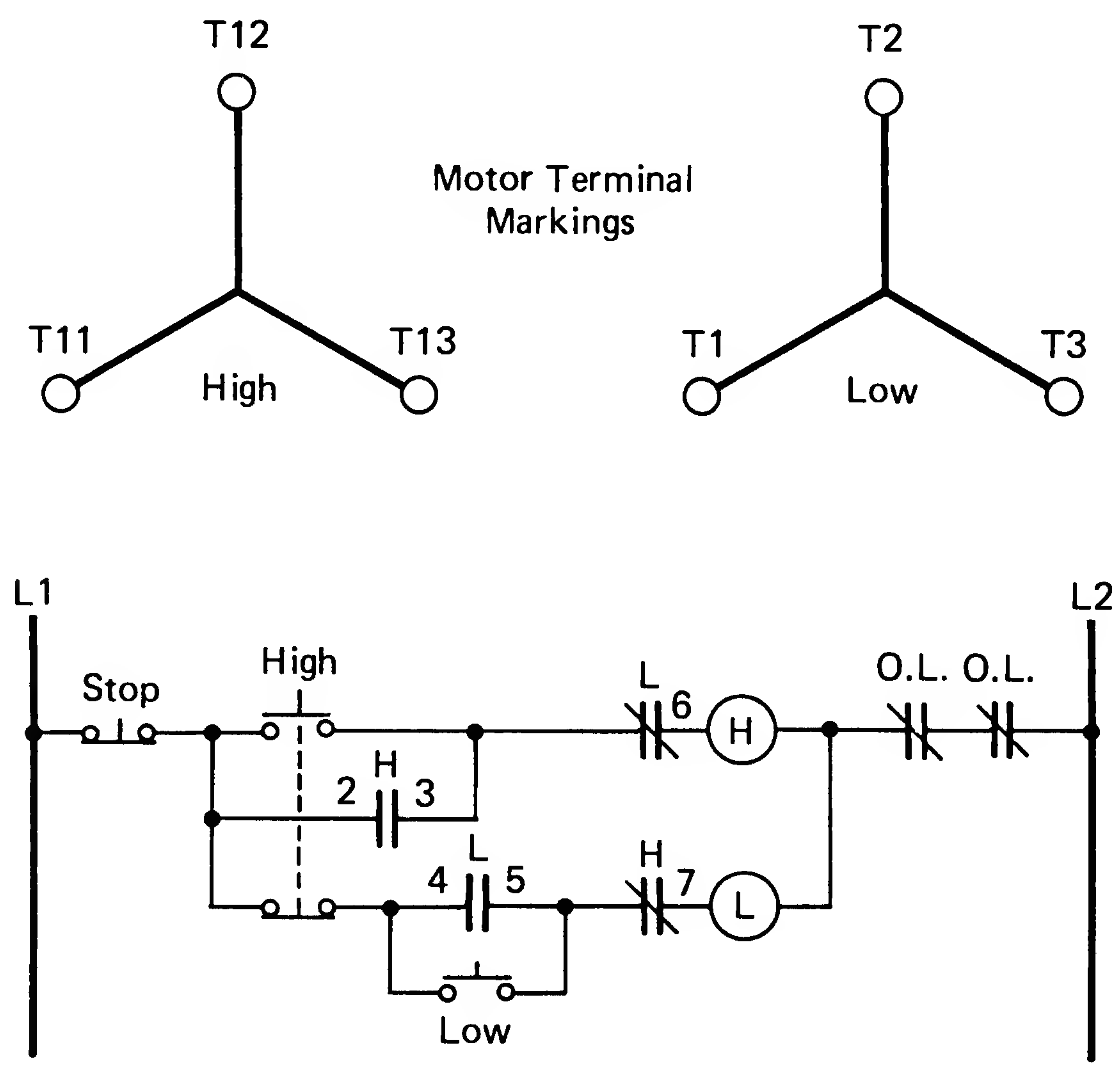


Fig. 4-85 (*con't.*)

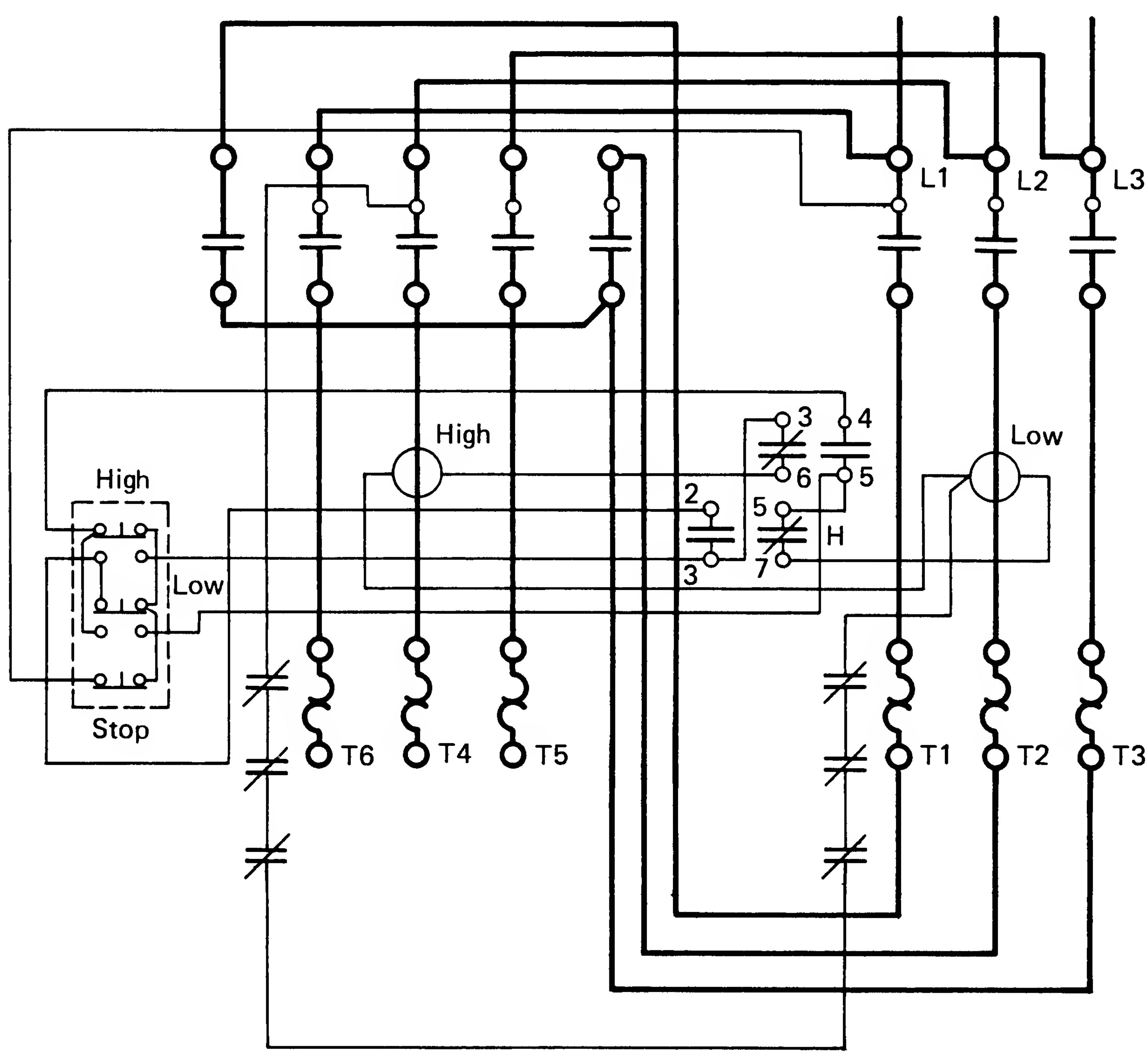
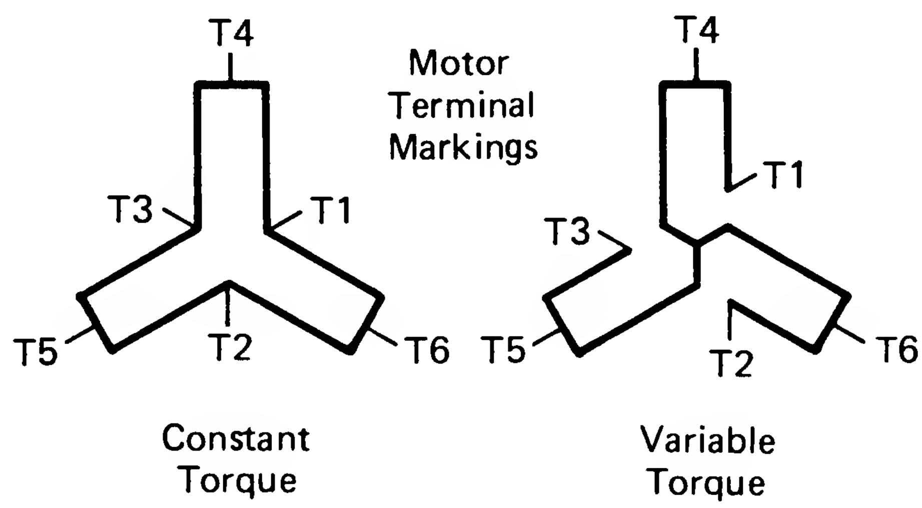


Fig. 4-86. Wiring diagram of a two-speed, single-winding, three-phase, squirrel-cage motor controller for constant torque or for variable torque. (*Allen-Bradley Co.*)

CONNECTIONS MADE BY STARTER			
Speed	Supply Lines L1 L2 L3	Open	Together
Low	T1 T2 T3	T4, 5, 6	None
High	T6 T4 T5	None	T1, 2, 3

Fig. 4-86. (*continued*)



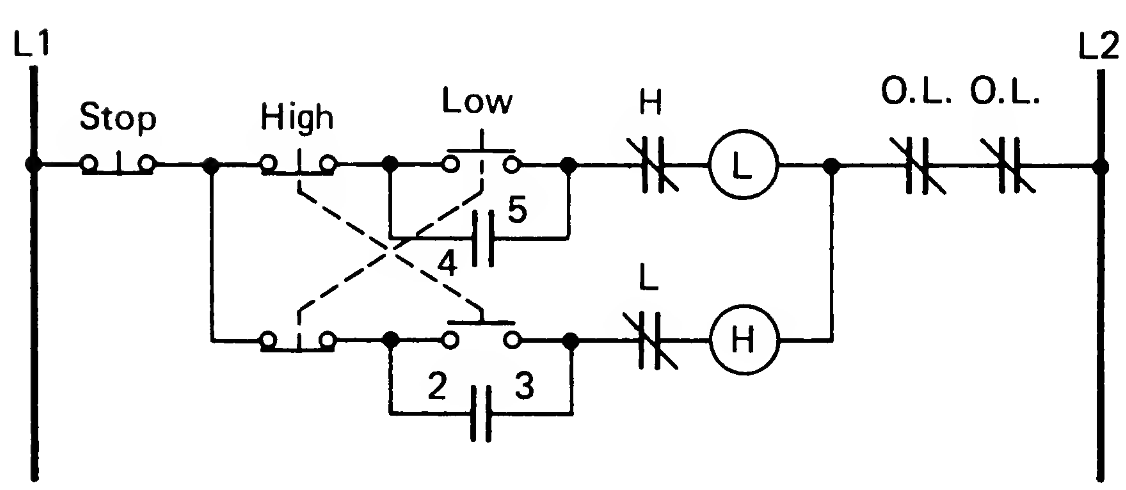
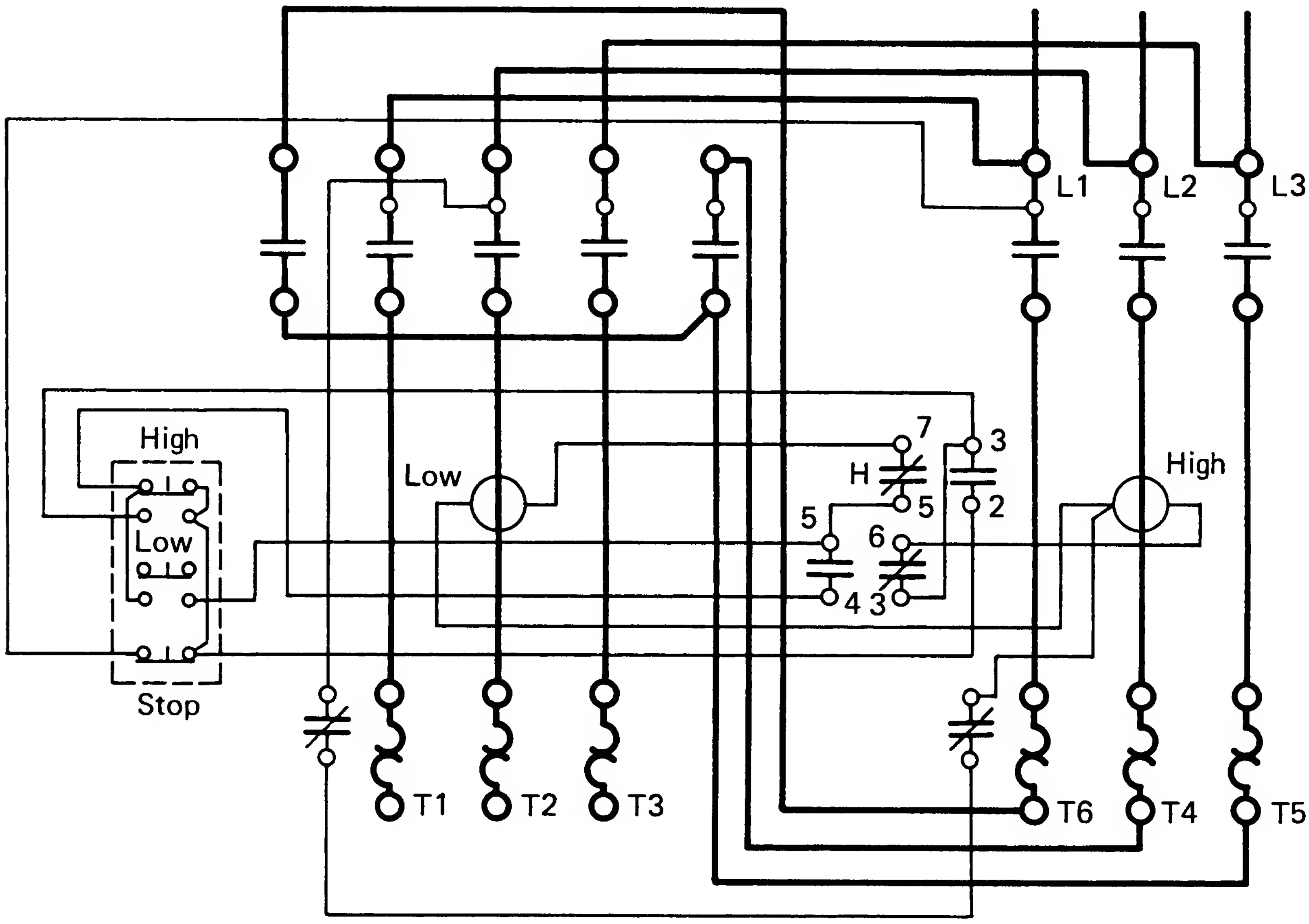
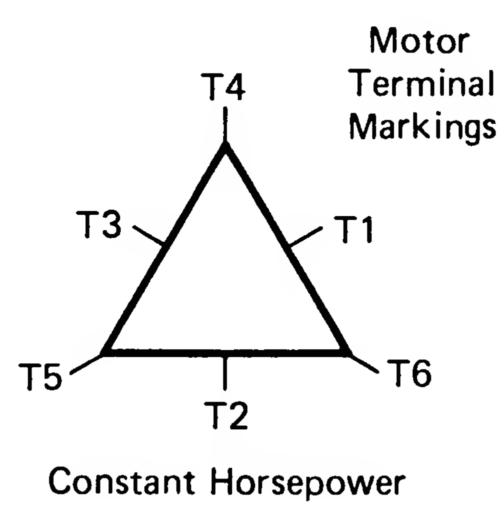


Fig. 4-87. Control circuit for starter in **Fig. 4-86.**

Figures 4-86 (*con't.*); 4-87



CONNECTIONS MADE BY STARTER			
Speed	Supply Lines L1 L2 L3	Open	Together
Low	T1 T2 T3	None	T4, 5, 6
High	T6 T4 T5	T1, 2, 3	None



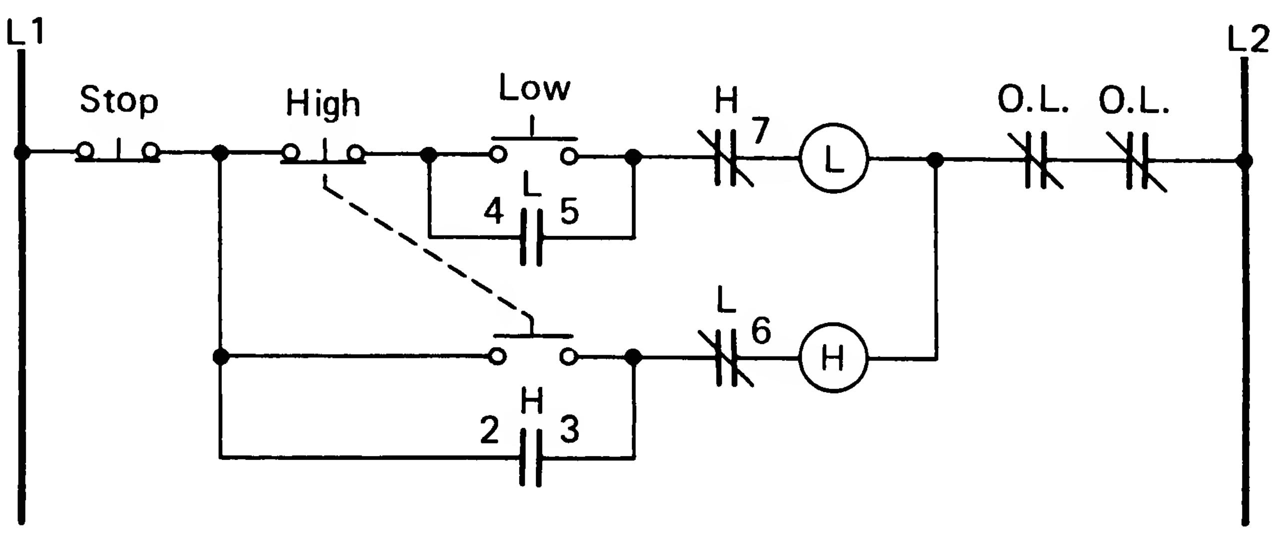


Fig. 4–88. Wiring diagram of a two-speed constant horsepower consequent pole motor starter. (*Allen-Bradley Co.*)

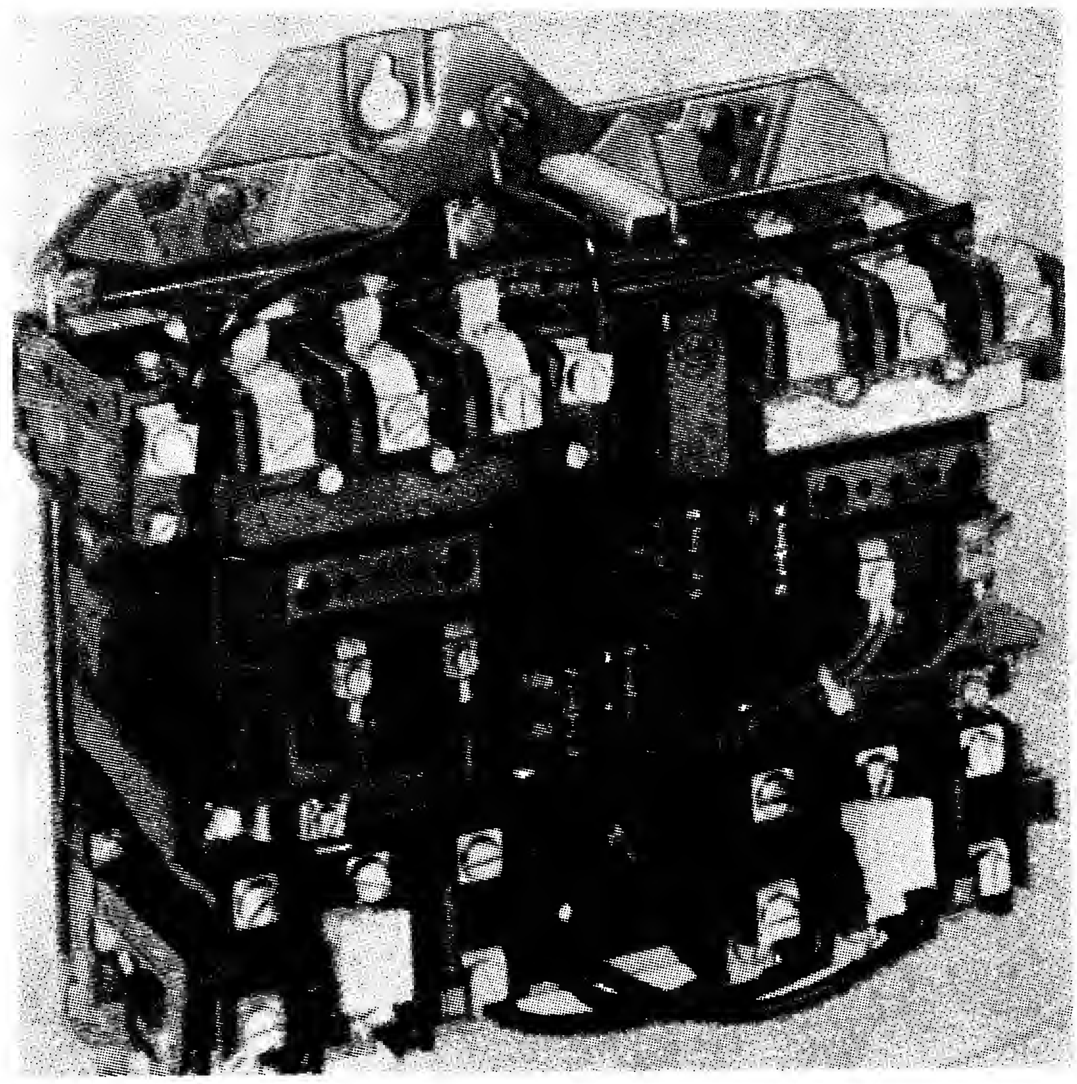
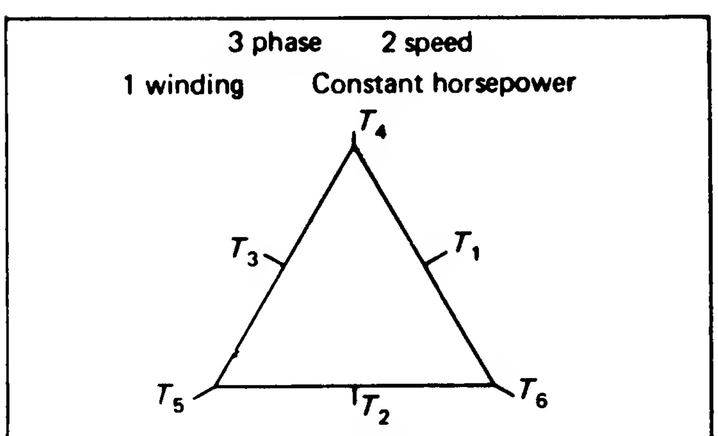
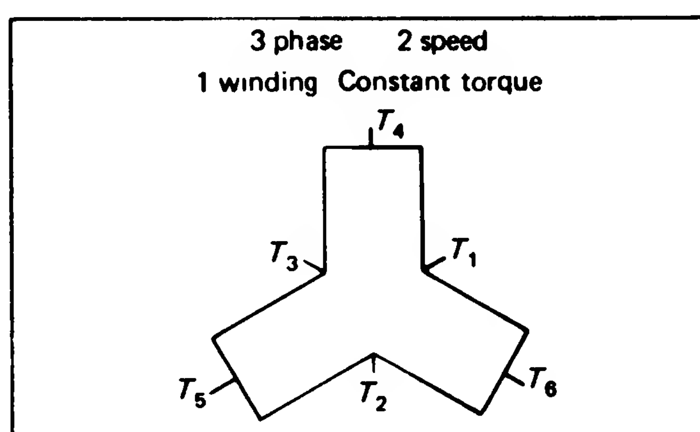


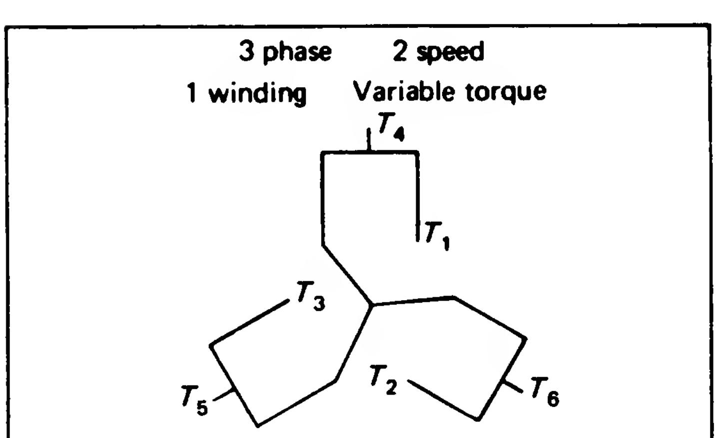
Fig. 4-89. A multispeed starter for consequent pole motors. (*Allen-Bradley Co.*)



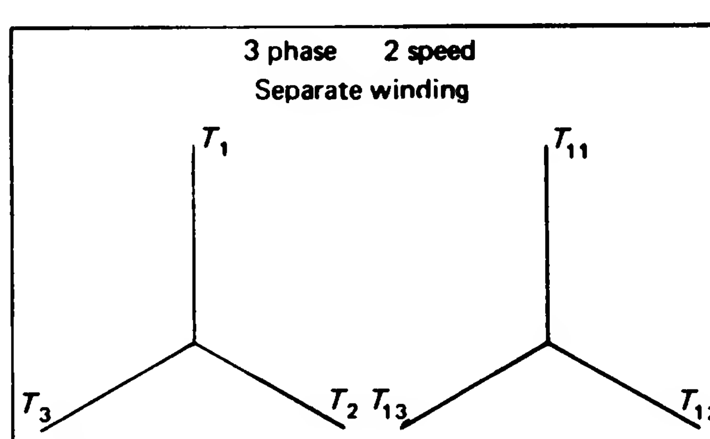
Speed	L1	L2	L3	Open	Together
Low	T_1	T_2	T_3		$T_{4,5,6}$
High	T_6	T_4	T_5	All others	



Speed	L1	L2	L3	Open	Together
Low	T_1	T_2	T_3	All others	
High	T_6	T_4	T_5		$T_{1,2,3}$

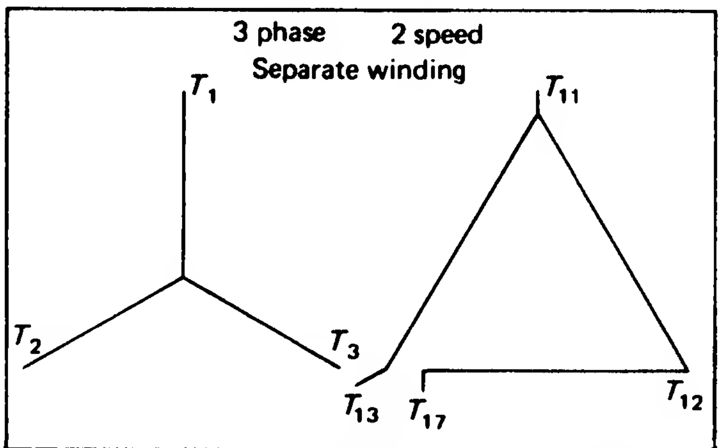


Speed	L1	L2	L3	Open	Together
Low	T_1	T_2	T_3	All others	
High	T_6	T_4	T_5		$T_{1,2,3}$

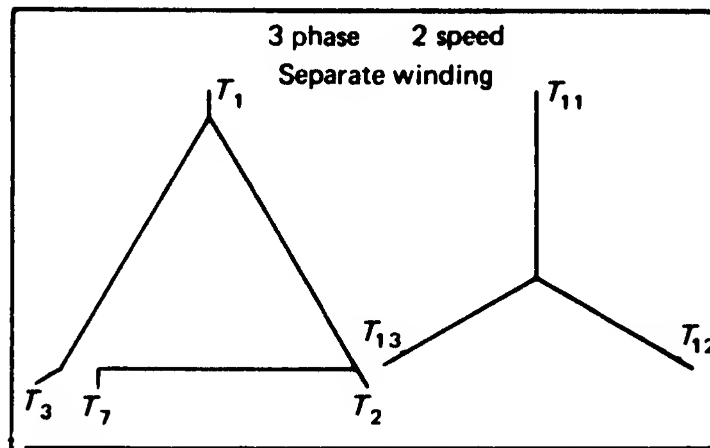


Speed	L1	L2	L3	Open
Low	T_1	T_2	T_3	All others
High	T_{11}	T_{12}	T_{13}	All others

Fig. 4-90. Two-speed motor connections.



Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3	All others
High	T_{11}	T_{12}	T_{13}, T_{17}	All others



Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3, T_7	All others
High	T_{11}	T_{12}	T_{13}	All others

Fig. 4-90. (*continued*)

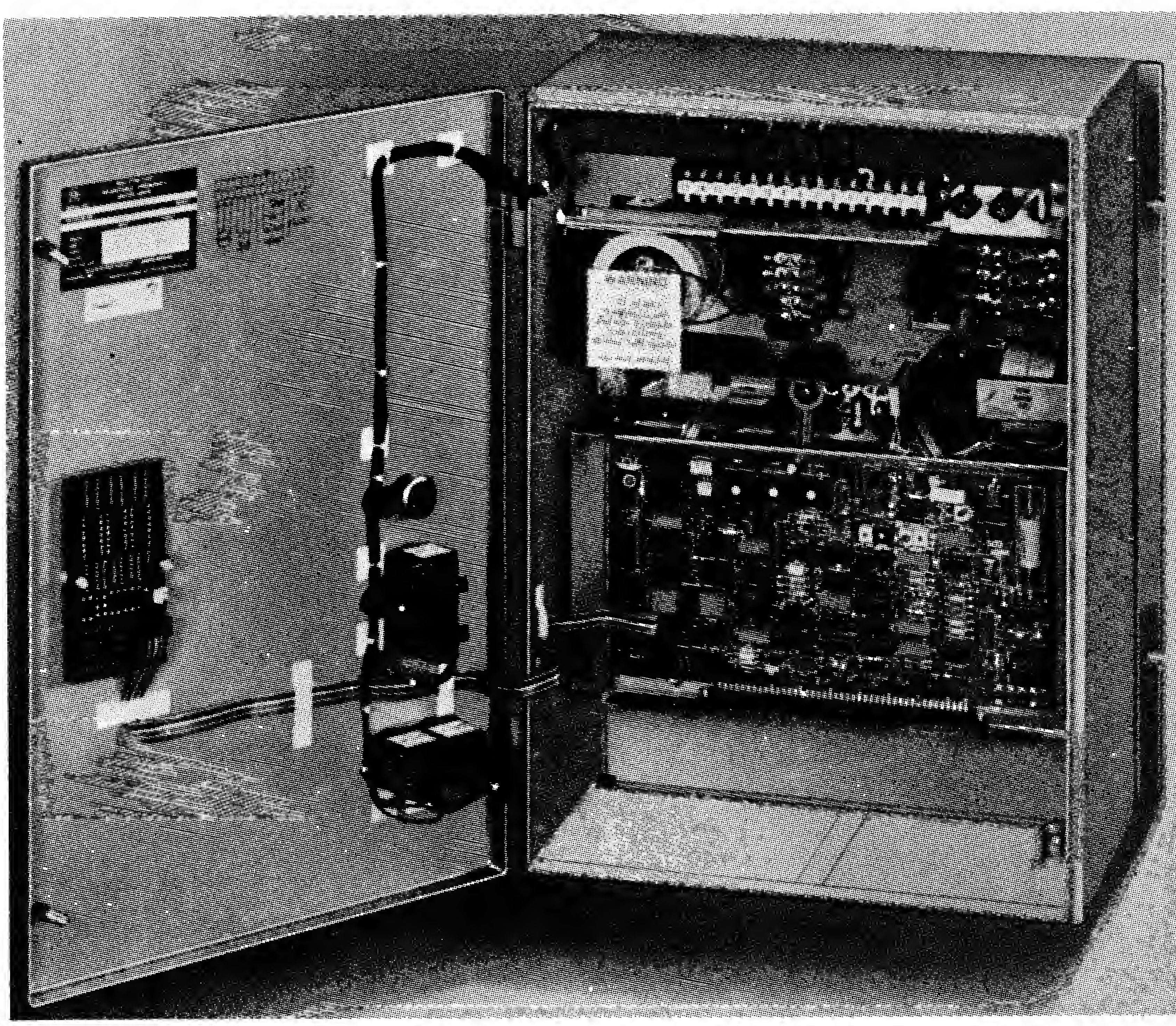


Fig. 4-91. A one-through-15-horsepower, adjustable-frequency controller. (*Allen-Bradley Co.*)

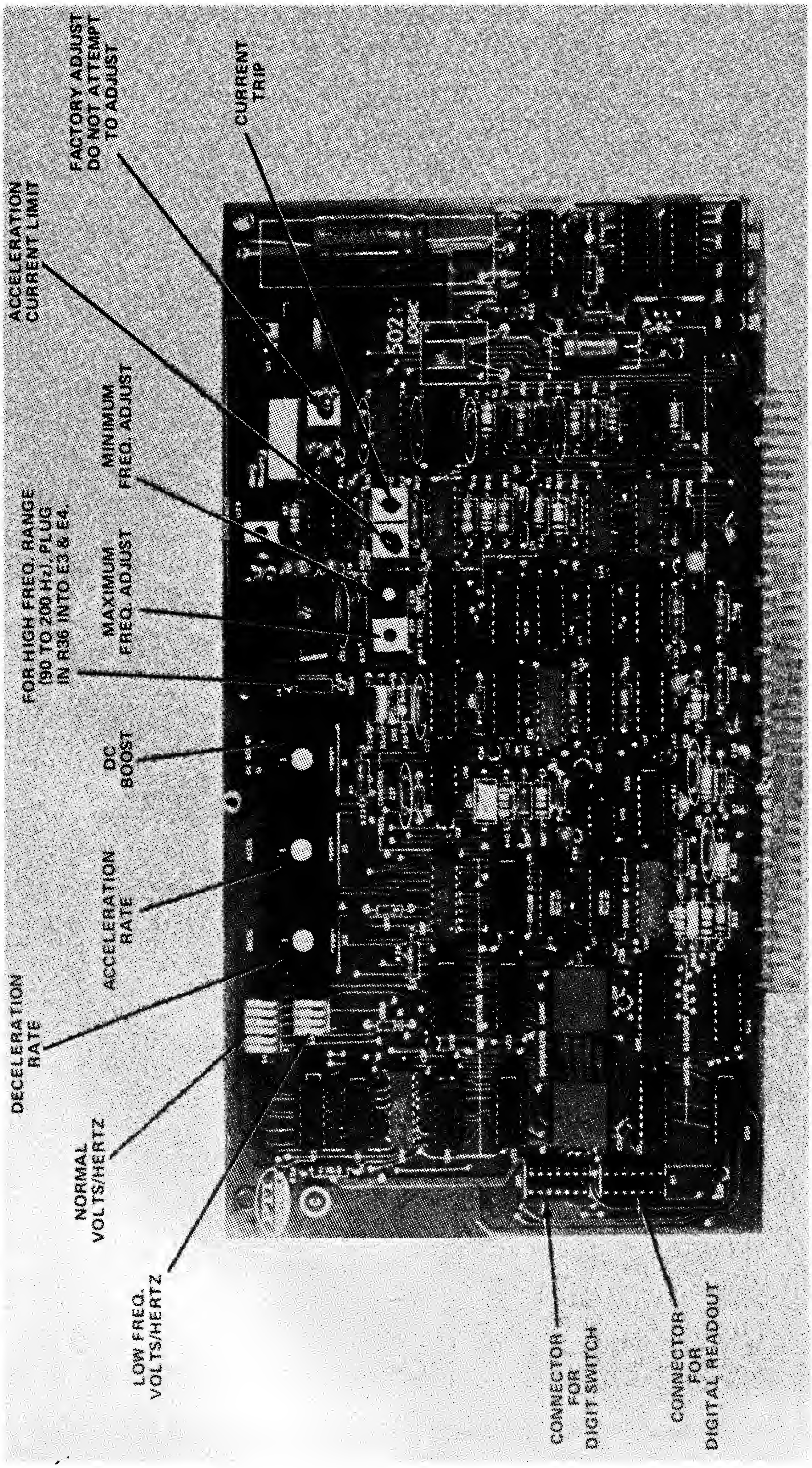


Fig. 4–92. Logic board for adjustable-frequency drive. (*Allen-Bradley Co.*)

Figure 4–92

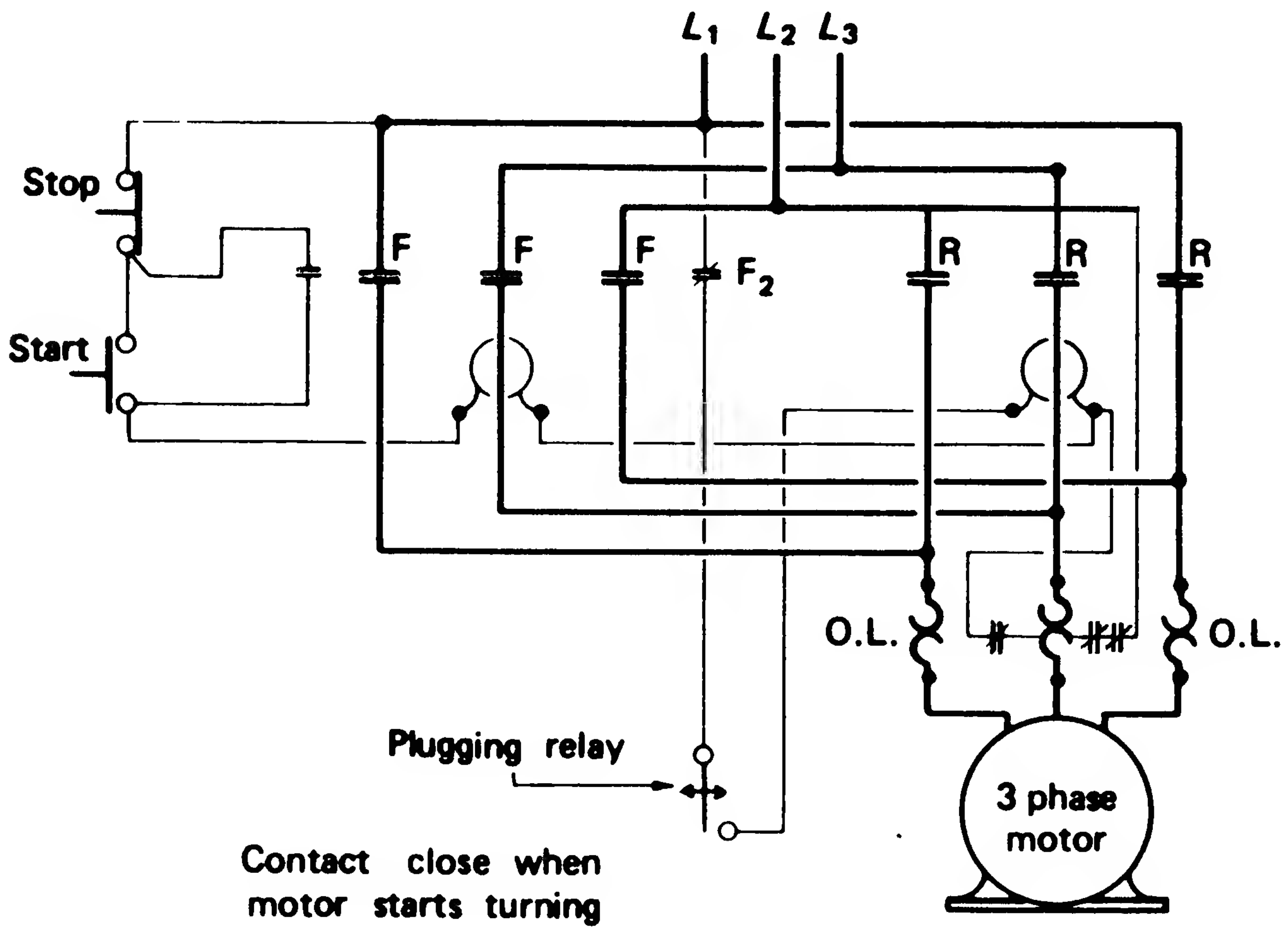


Fig. 4-93. A controller using a plugging relay for braking.

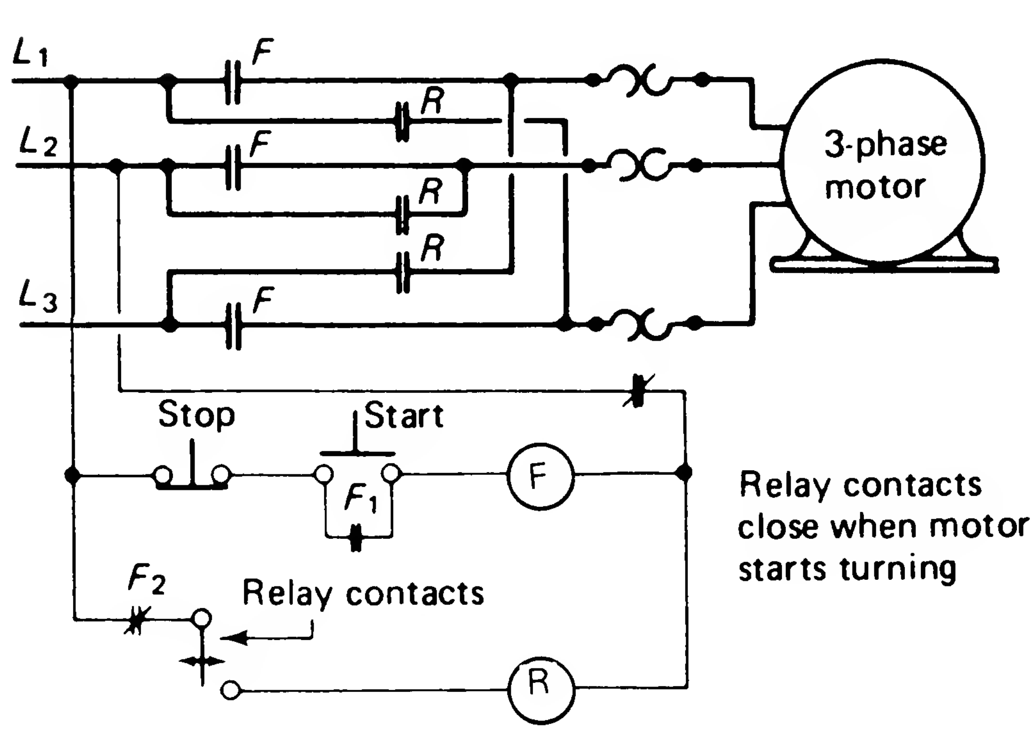


Fig. 4-94. A line diagram of a controller with a plugging relay.

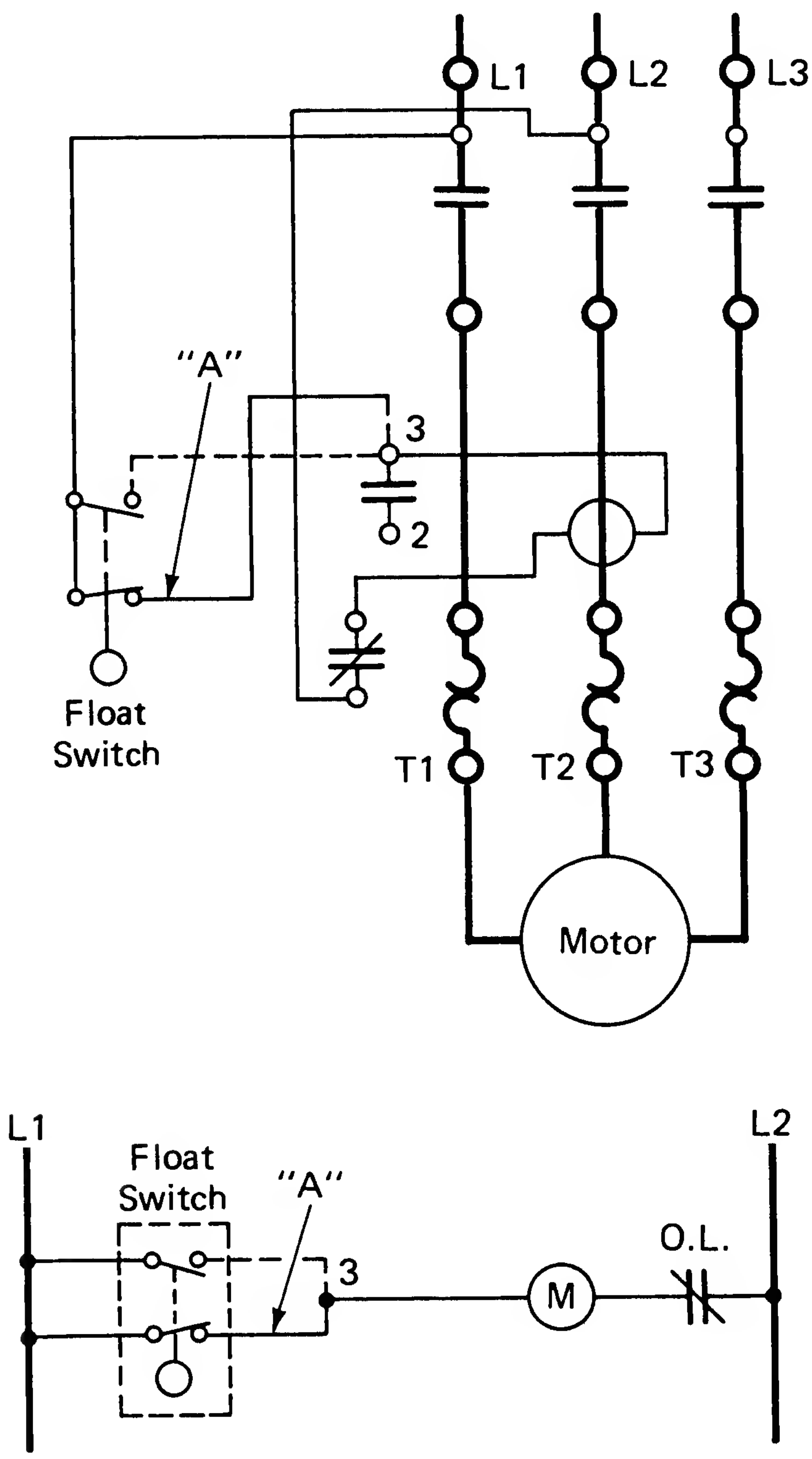


Fig. 4–95. A three-phase starter controlled by a float switch. (*Allen-Bradley Co.*)

Figure 4–95

CHAPTER 5

Direct-current Armature Winding

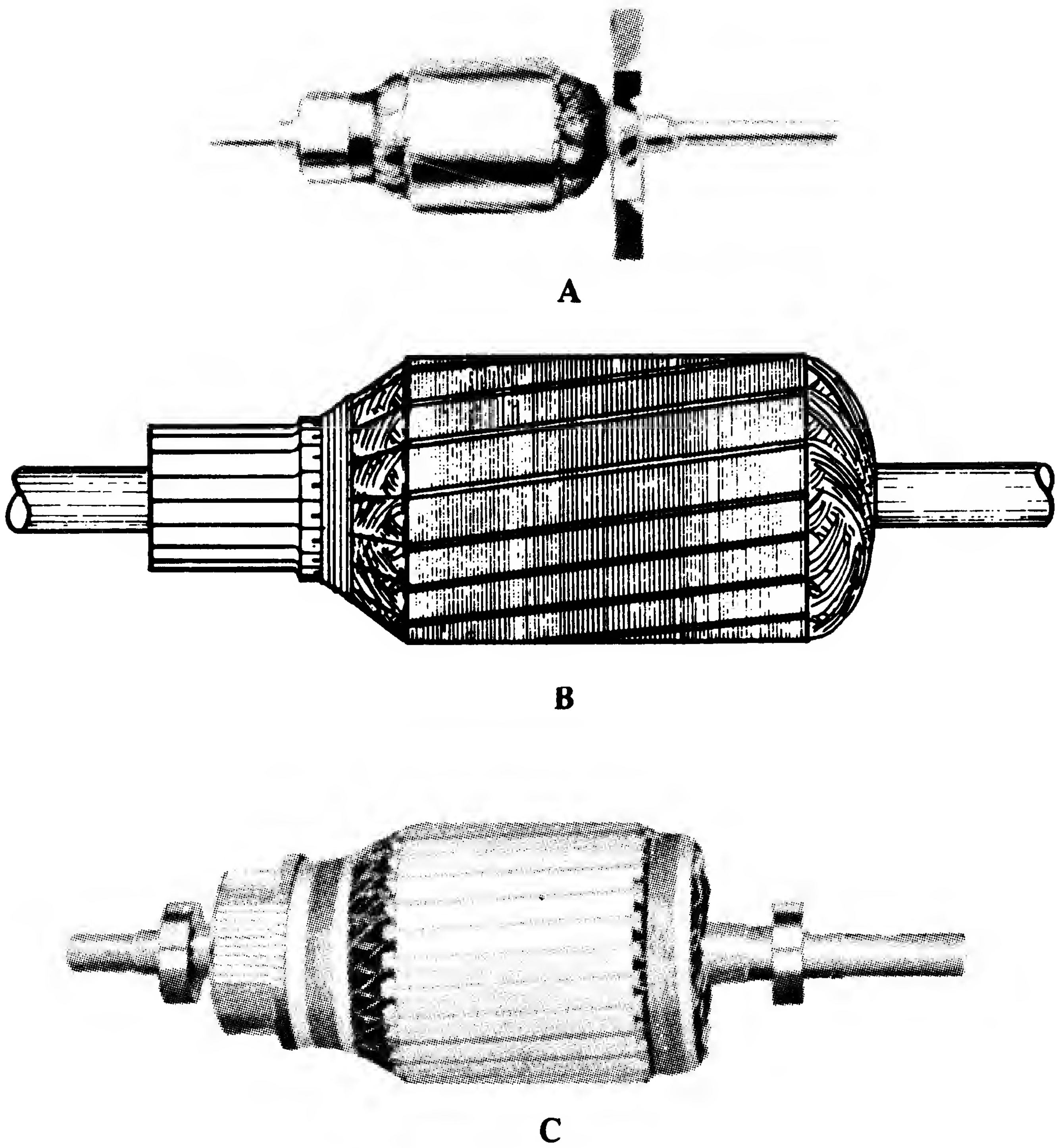


Fig. 5-1. Different types of dc armatures.

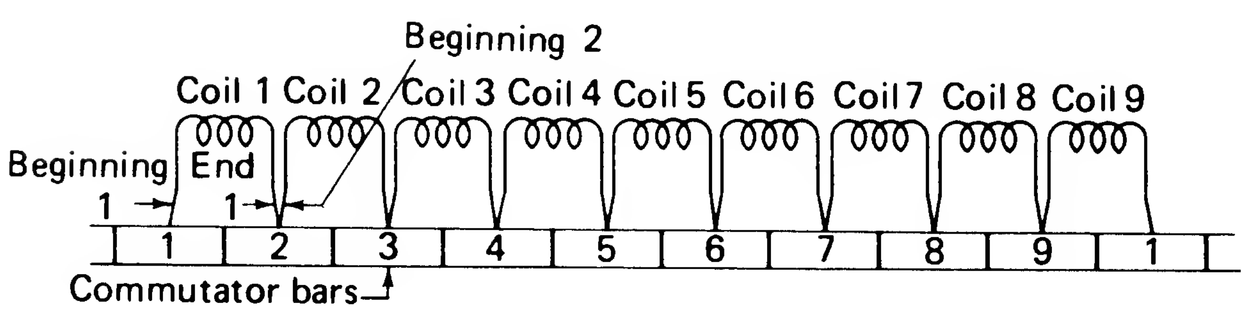


Fig. 5-2a. A schematic diagram of a simple loop winding that consists of nine coils and nine commutator bars. The end lead of each coil and the beginning lead of the next coil are placed in the same commutator bar. The end lead of the last coil is placed in the same bar as the beginning lead of the first coil.

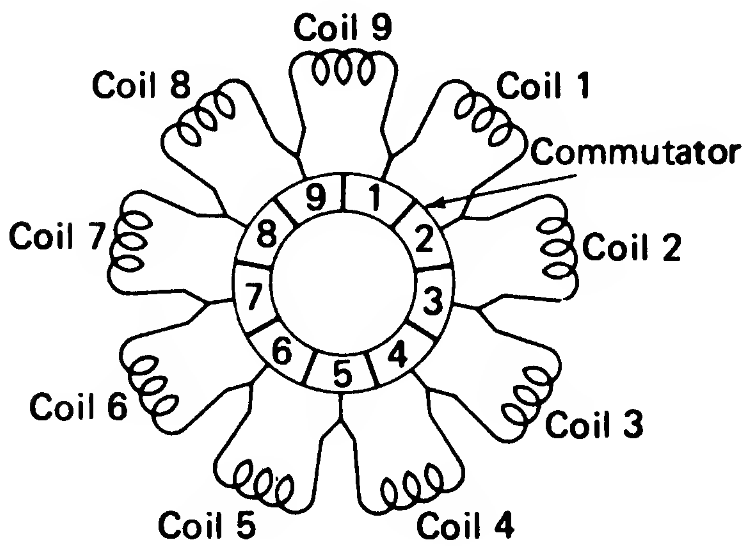
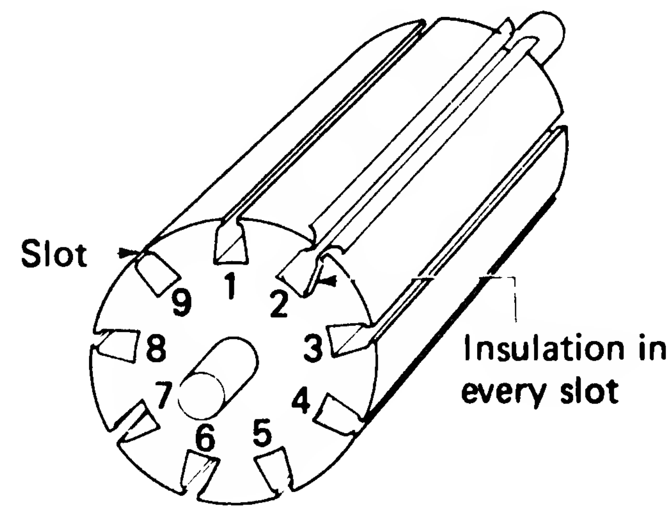


Fig. 5-2b. A circular schematic diagram showing all the coils of a nine-coil armature connected to the commutator bars.

Fig. 5-3. Slots in the armature into which the coils are wound.



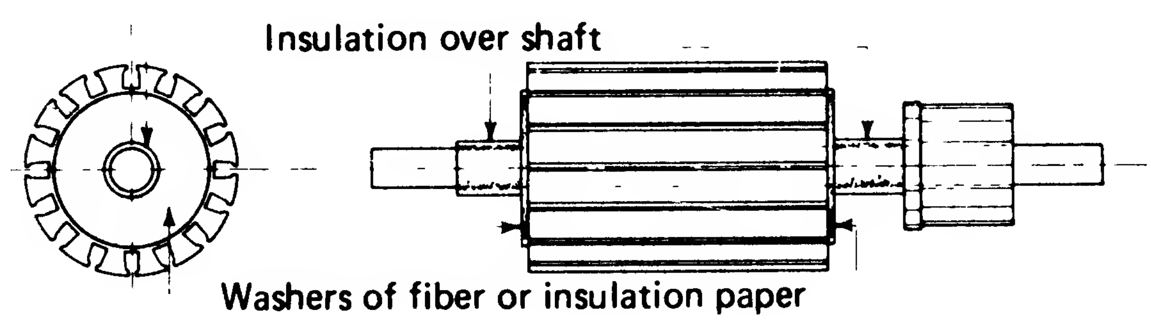


Fig. 5-4. In addition to the slot insulation, the insulation shown above is necessary to protect the winding from grounding.

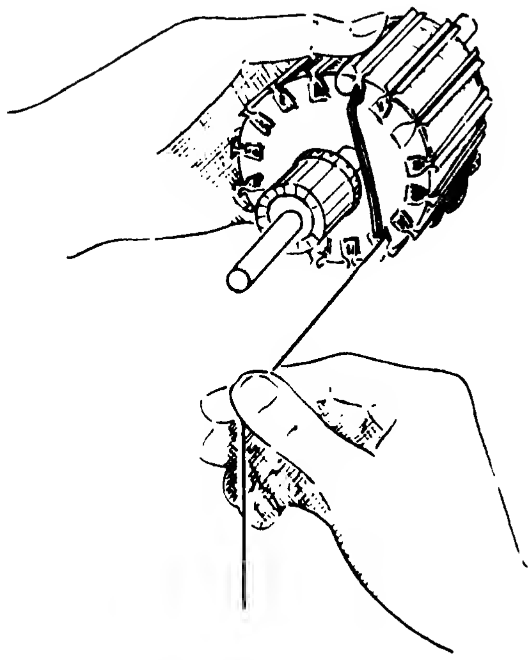


Fig. 5-5. A small armature can be held in one hand during winding.

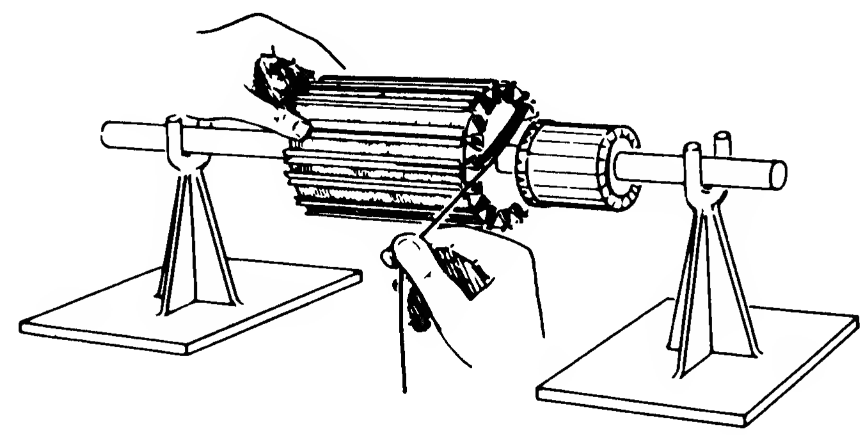


Fig. 5-6. Large armatures are supported by horses during winding.

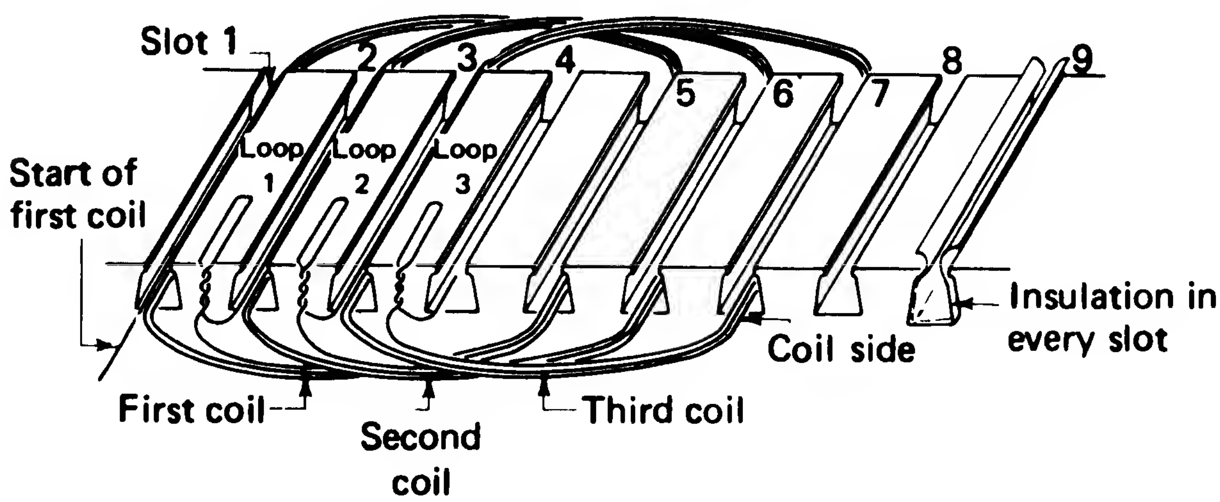


Fig. 5-7. The start of a loop winding. The entire armature is wound before the loops are connected to the commutator. Note that the first coil is wound into slots *1* and *5*. This is the pitch or span of the coil.

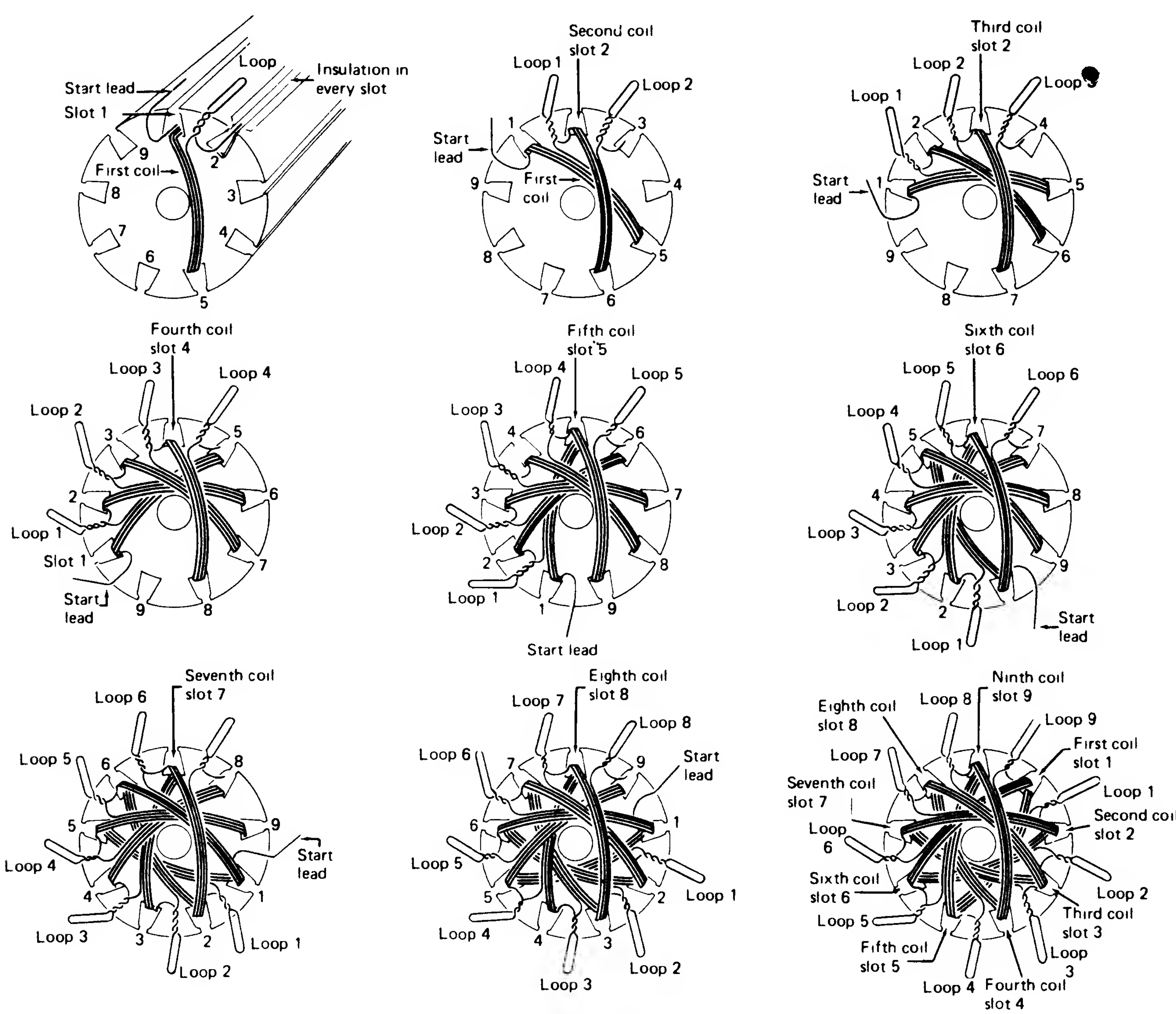


Fig. 5-8. Steps in winding the coils of a nine-slot armature.

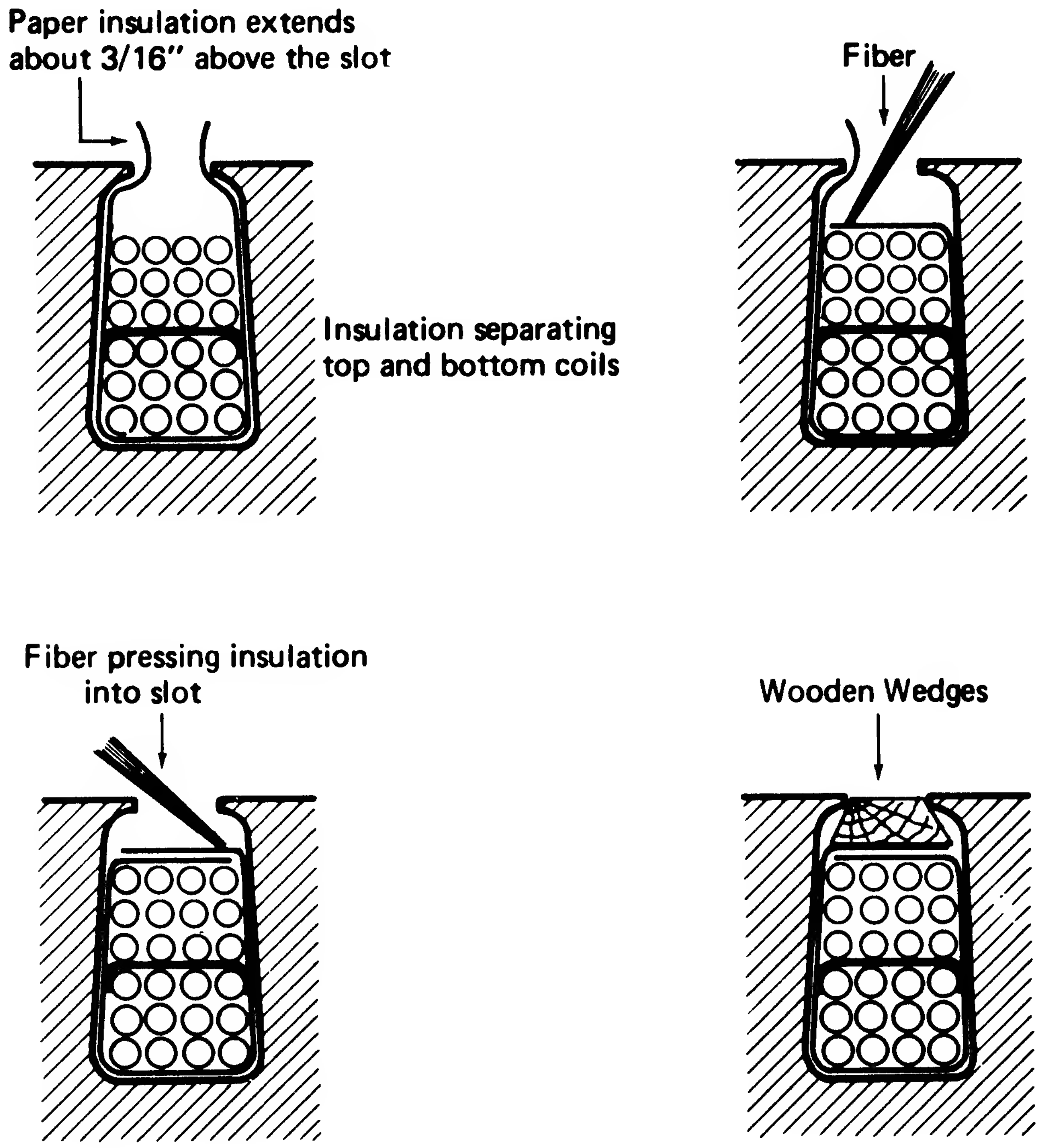


Fig. 5-9. A method of folding insulation into slot and locking it in place with a wooden wedge.

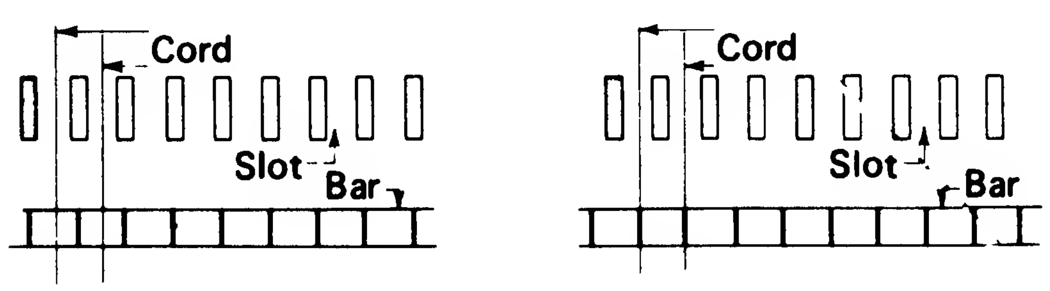


Fig. 5-10. A simple method of determining the alignment of slot and commutator bar.

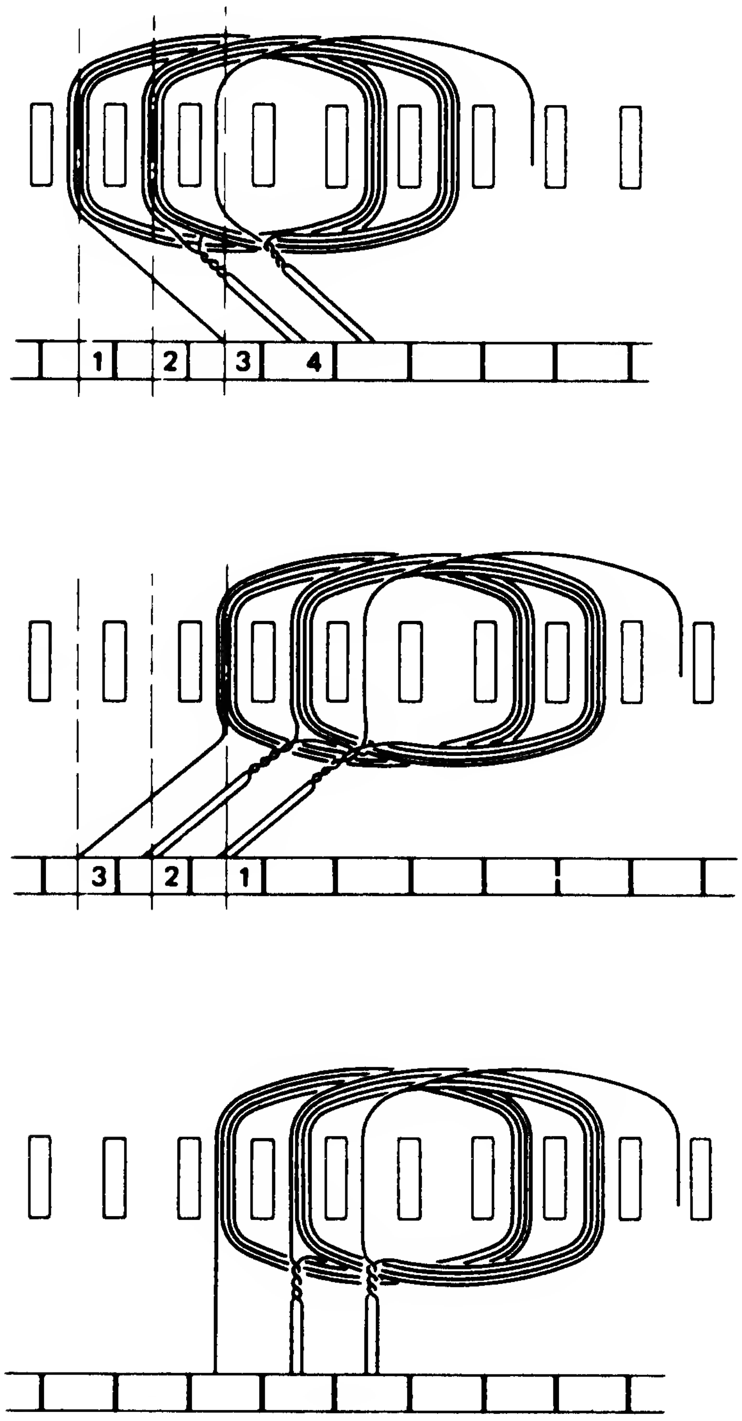


Fig. 5-11. Three conditions of lead swing.

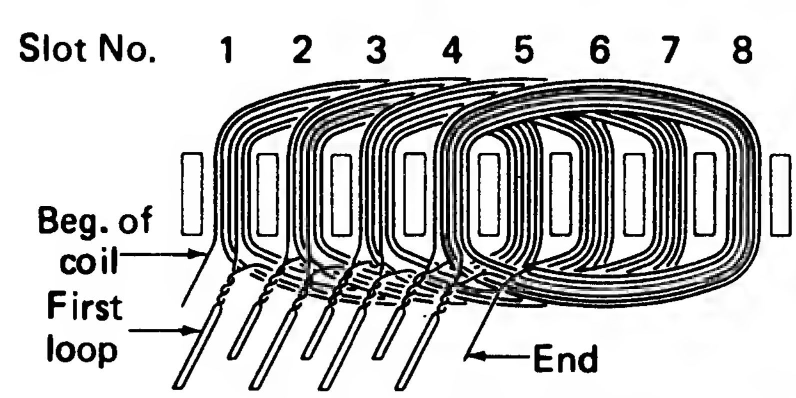


Fig. 5-12. A two-coil-per-slot winding with short and long loops for identification.

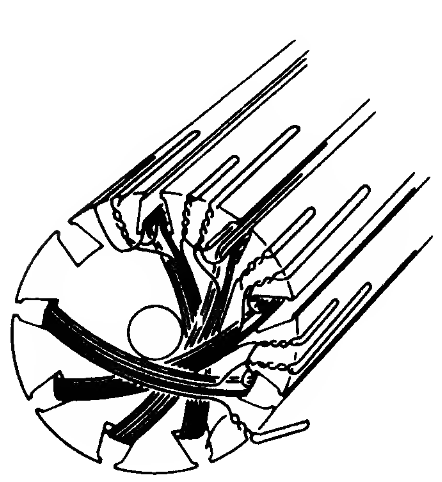


Fig. 5-13. A loop armature having twice as many loops as slots after four coils have been wound.

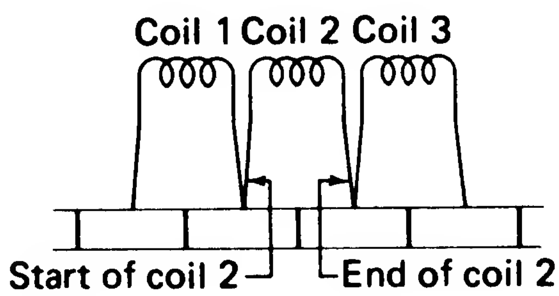


Fig. 5-14. A simplex lap winding in which the start and end of a coil are connected to adjacent bars.

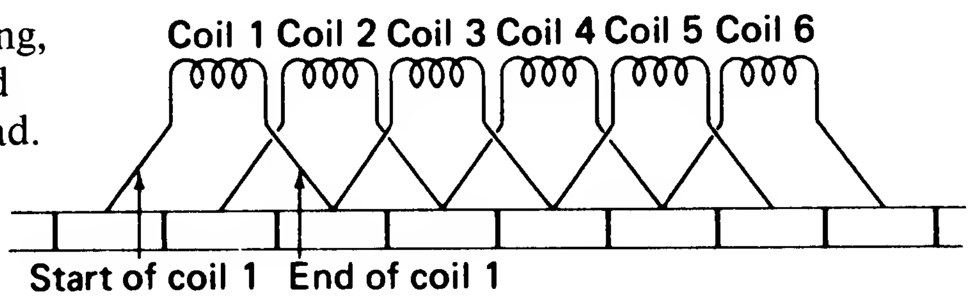


Fig. 5-15. In a duplex lap winding, the end lead of each coil is connected two bars away from the beginning lead.

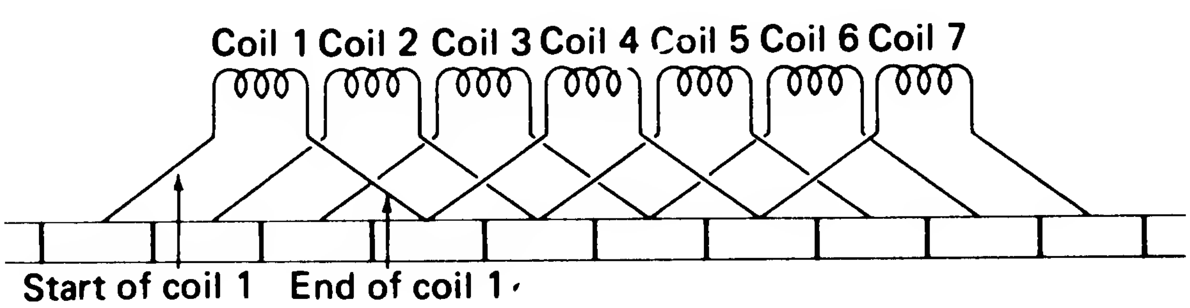


Fig. 5-16. In a triplex lap winding, the end lead of each coil is connected three bars away from the beginning lead.

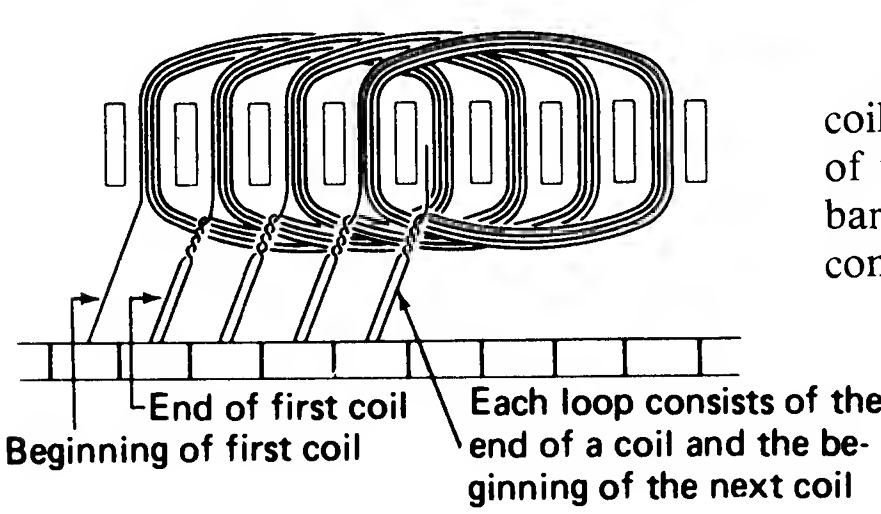


Fig. 5-17. A lap winding with one coil per slot has the beginning and end of the same coil connected to adjoining bars. The loops are connected to the commutator bars in succession.

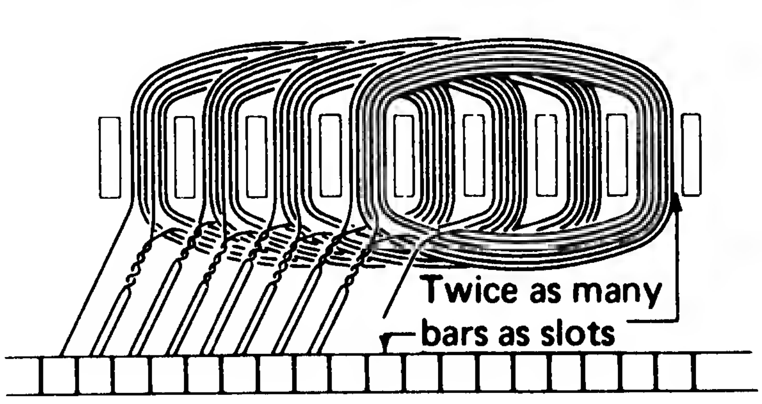


Fig. 5-18. A lap winding with two coils per slot. The beginning and end of each coil is connected to adjoining bars.

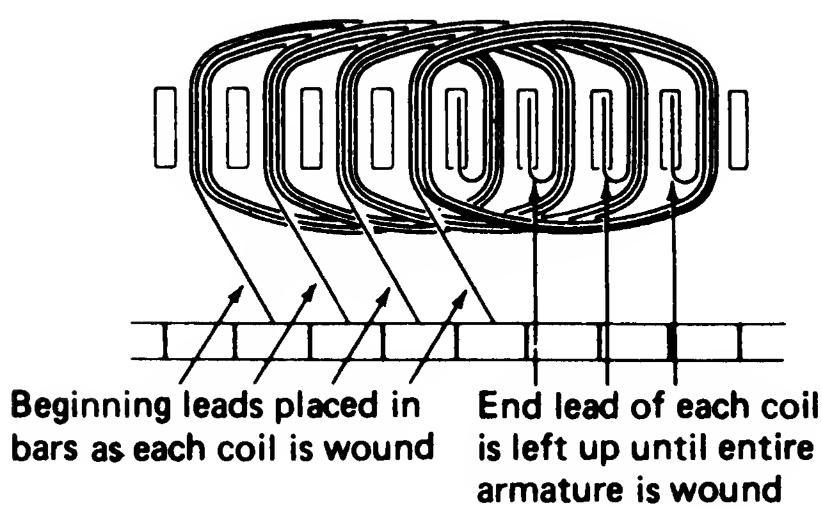


Fig. 5-19. A lap winding of one coil per slot with beginning leads in place.

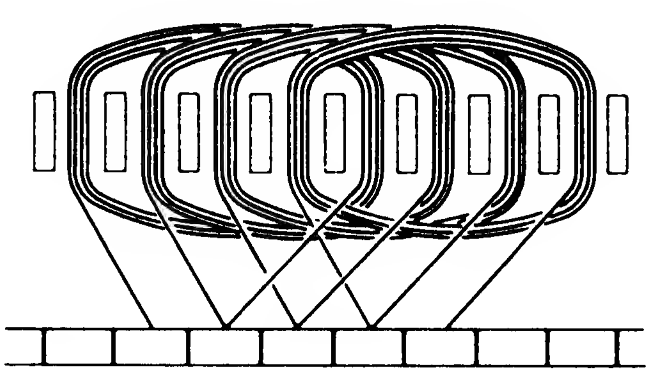


Fig. 5-20. A lap winding of one coil per slot after the end leads are placed in the commutator bars.

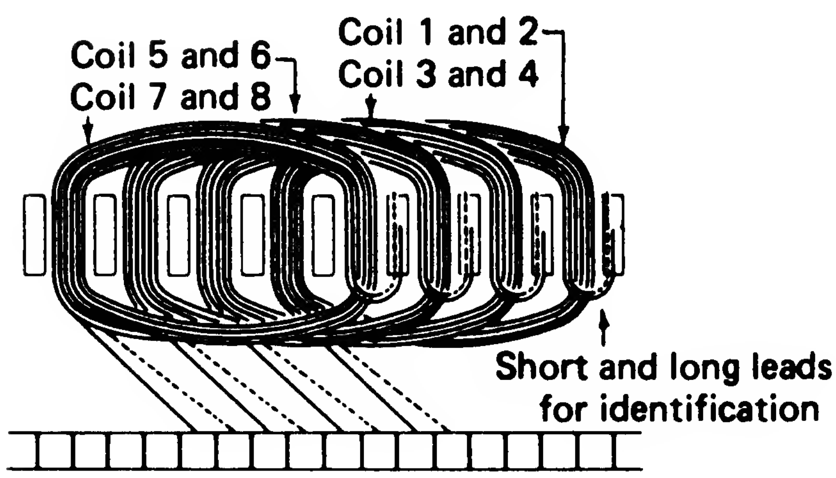


Fig. 5-21. A method of winding an armature having two coils per slot. The bottom or beginning leads are placed in the commutator bars as each coil is wound. The top leads are placed in the bars after the armature is wound.

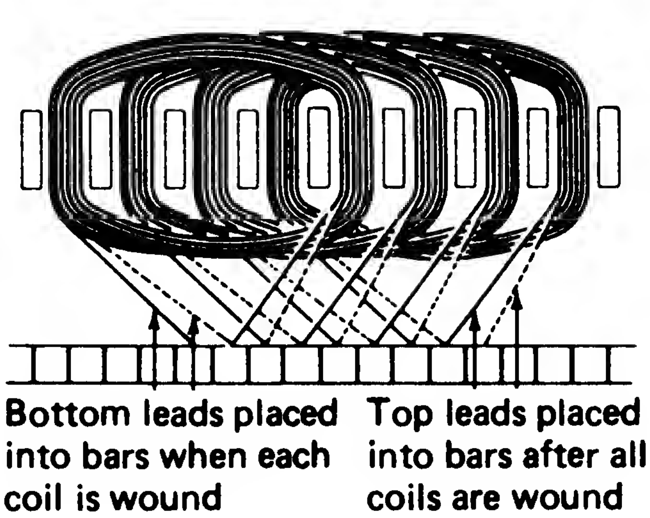


Fig. 5-22. The connections after the top leads are placed in the bars to produce a simplex lap winding with two coils in each slot.

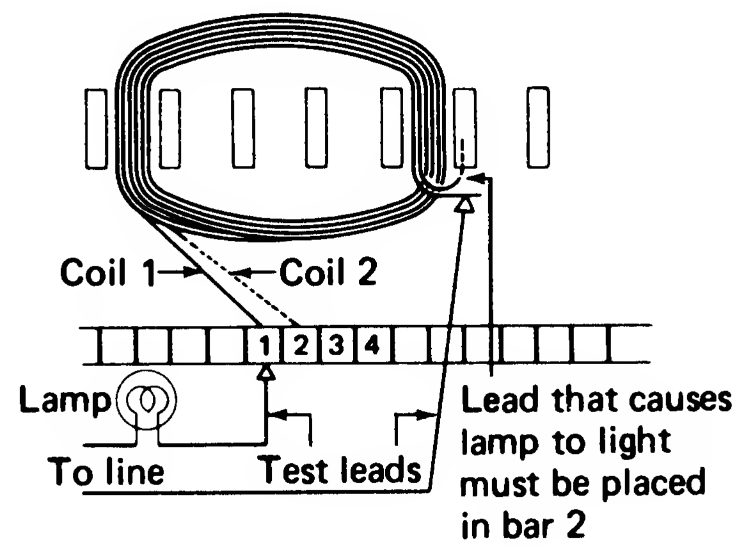


Fig. 5-23. Lamp method of determining in which bars top leads must be placed to produce a simple lap windinng.

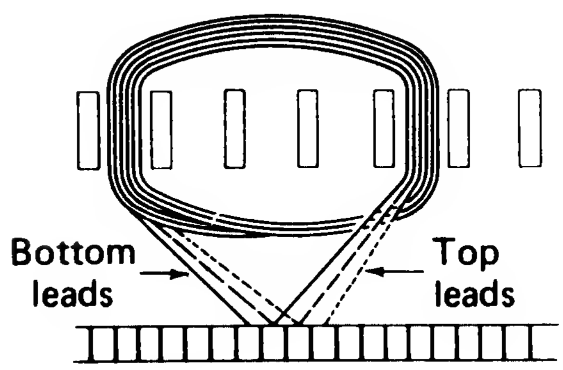


Fig. 5-24. A lap winding with three coils per slot.

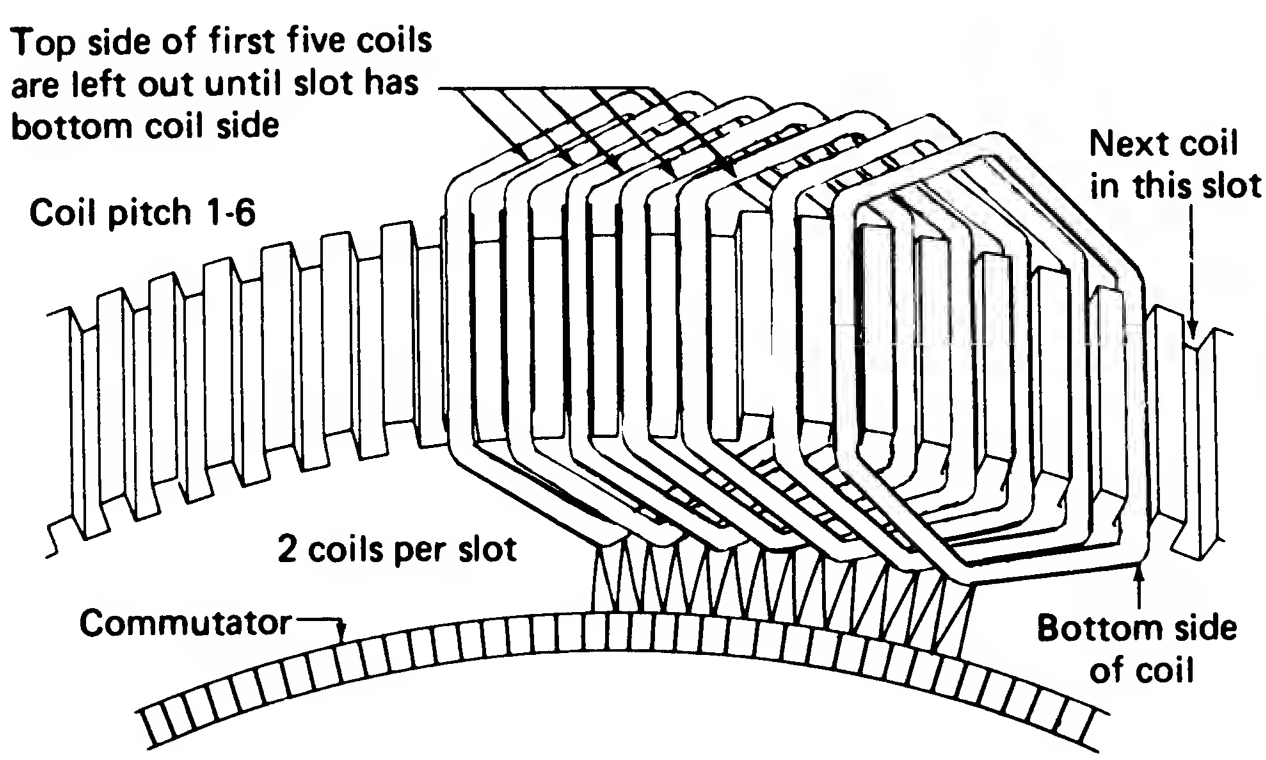
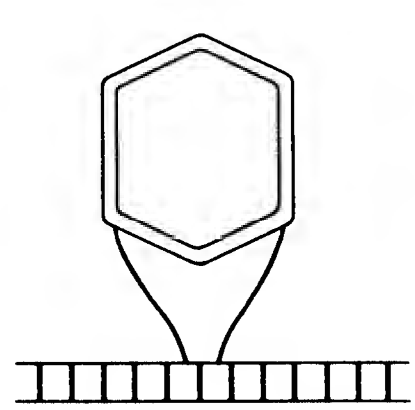


Fig. 5-25. A lap winding with two coils per slot.

Fig. 5-26. In a lap winding leads face each other and are connected to adjacent bars.



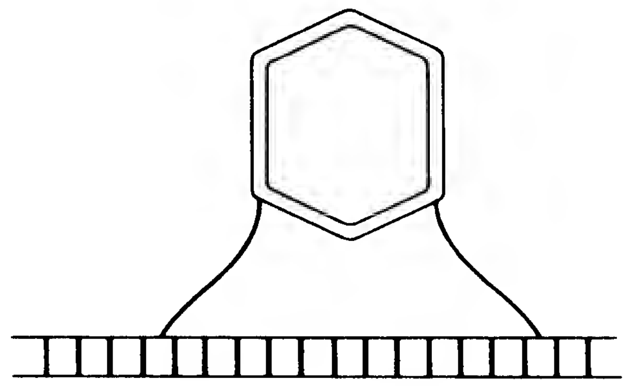


Fig. 5-27. In a wave winding, leads face away from one another and must be a definite number of commutator bars apart.

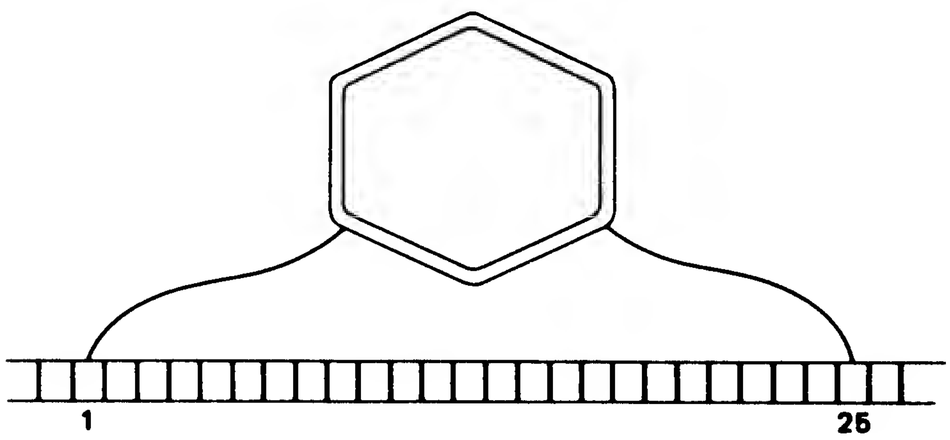


Fig. 5-28. Lead connections for a four-pole, 49-bar armature. According to the formular, the leads should be 24 bars apart; hence, they are placed in bars *1* and *25*.

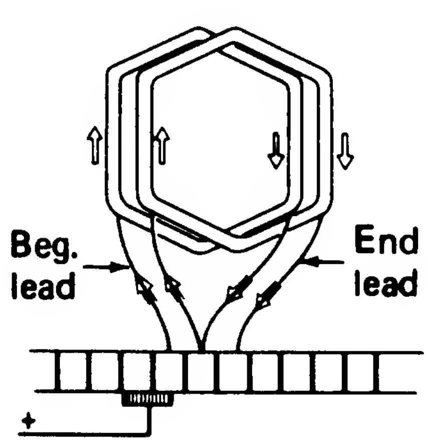


Fig. 5-29. A simplex progressive lap winding. The current flows in a clockwise direction.

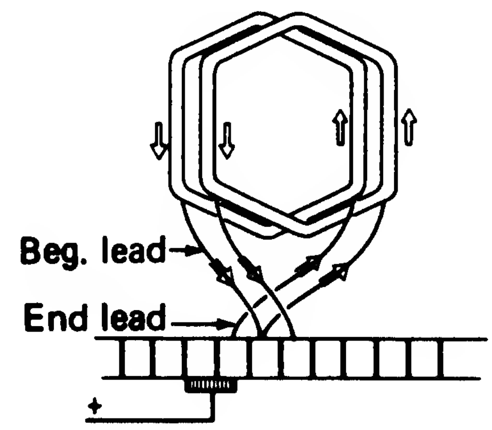


Fig. 5-30. A retrogressive lap winding. The leads cross one another even though they are connected to adjacent bars. The current flows in a counterclockwise direction.

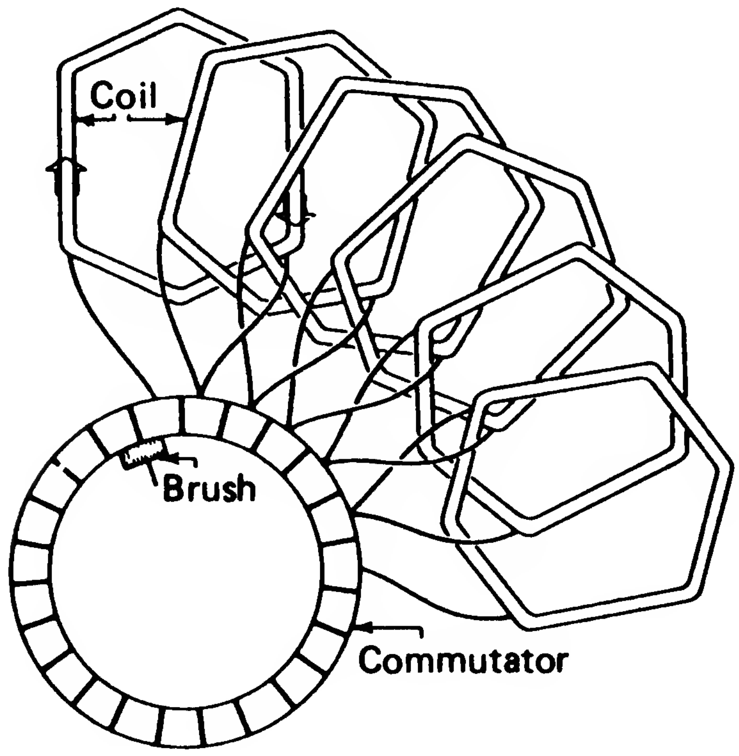


Fig. 5-31. A simplex, progressive lap winding.

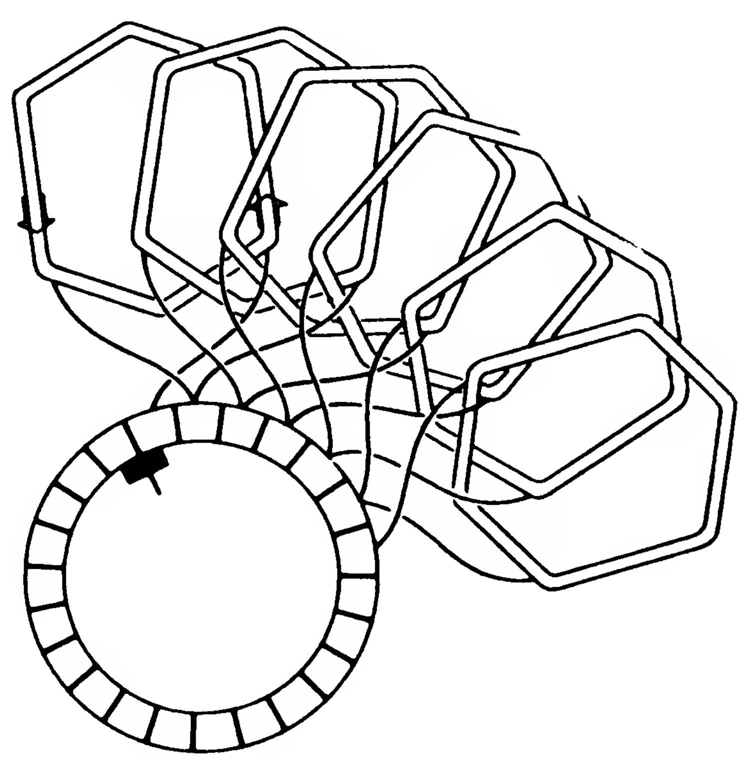


Fig. 5-32. A simplex, retrogressive lap winding.

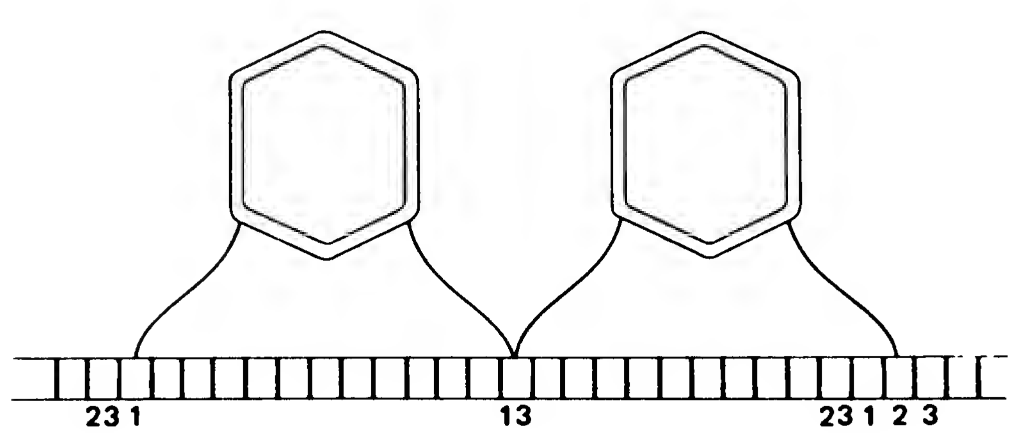


Fig. 5-33. A four-pole, simplex, progressive wave winding with a commutator pitch of 1 and 13. The current travels through two coils before reaching the bar adjacent to the start.

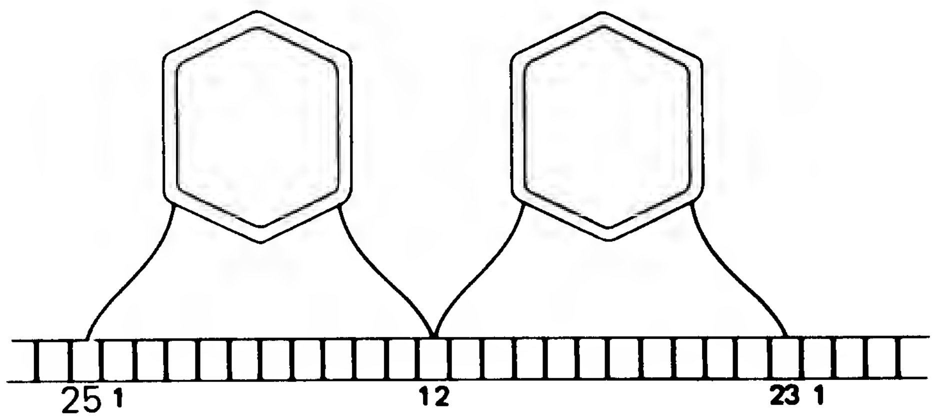


Fig. 5-34. A four-pole, simplex, retrogressive wave winding with a commutator pitch of 1 and 12.

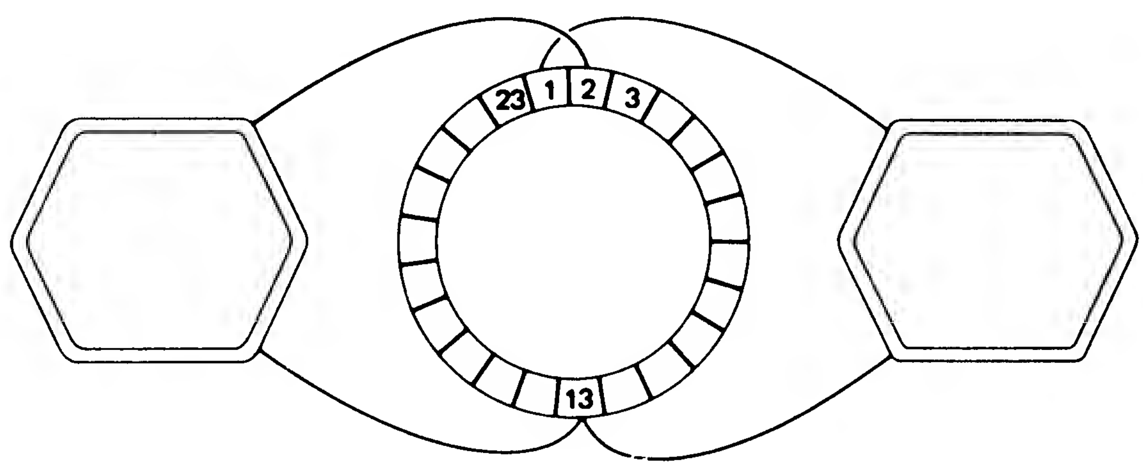


Fig. 5-35. A four-pole, simplex, progressive wave winding with a commutator pitch of 1 and 13.

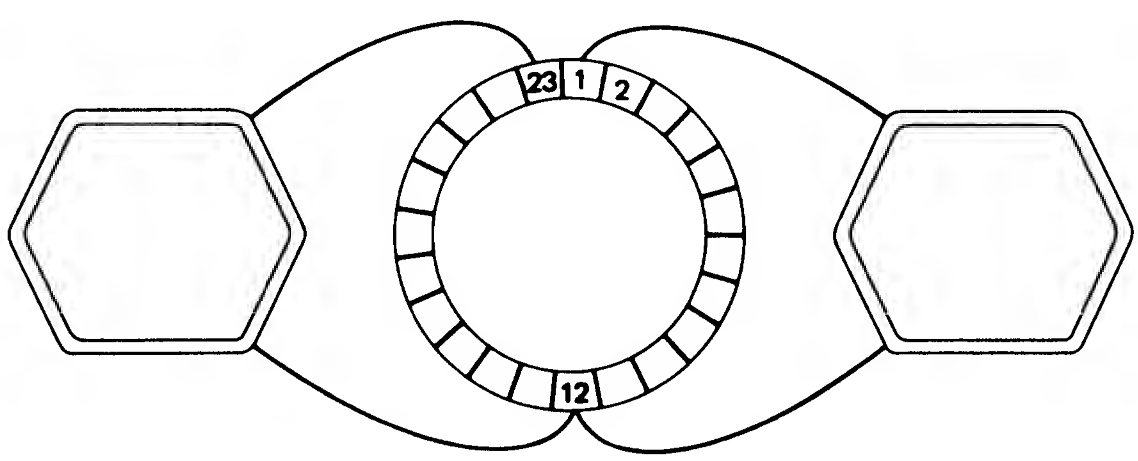


Fig. 5-36. A four-pole, simplex, retrogressive wave winding with a commutator pitch of 1 and 12.

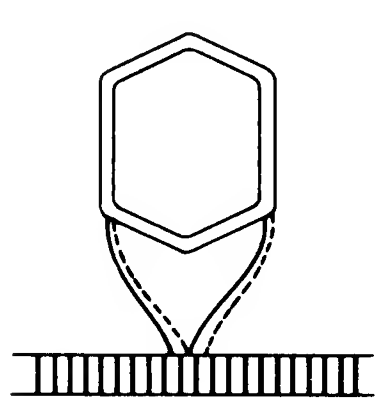


Fig. 5-37. Two coils of a progressive lap winding.

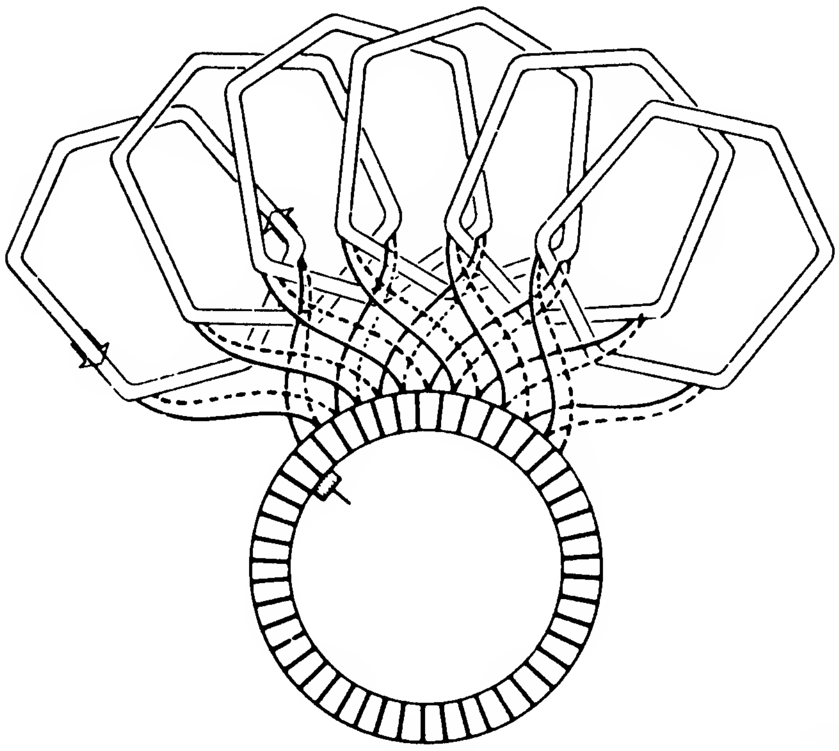


Fig. 5-38. Several coils of a retrogressive lap winding with two coils per slot.

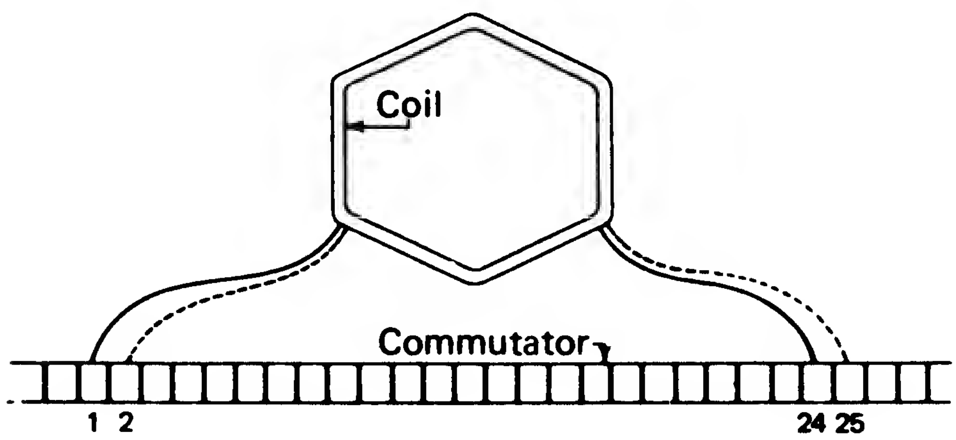


Fig. 5-39. Wave-wound coils.

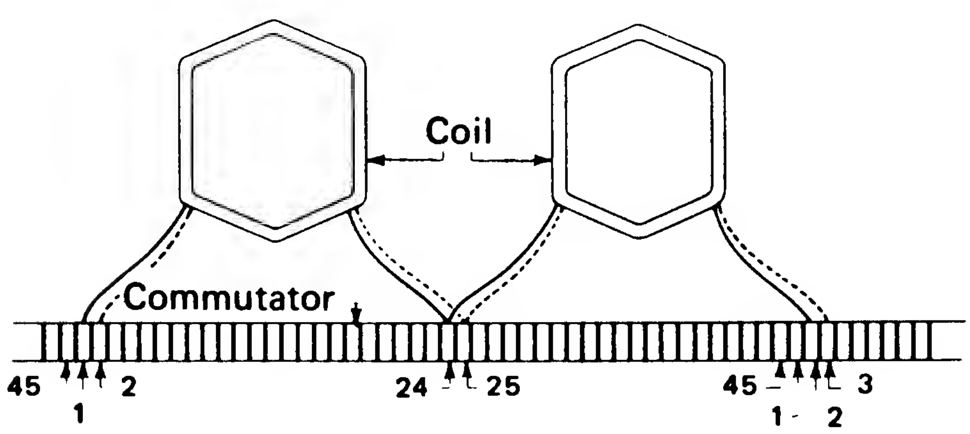


Fig. 5-40. A progressive wave winding, two coils per slot.

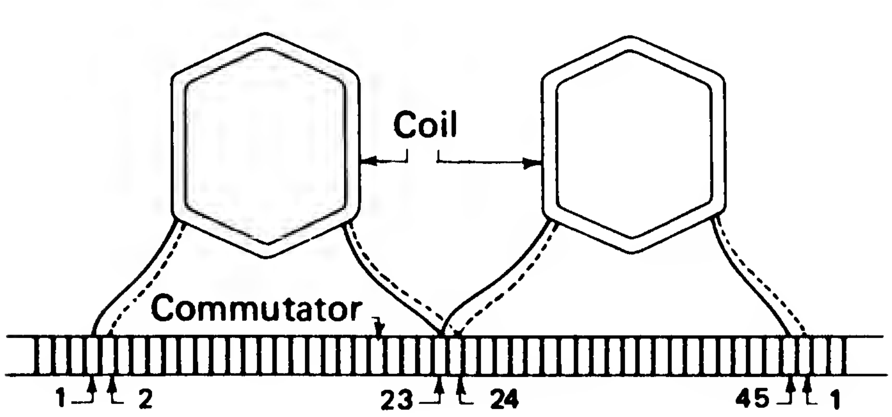


Fig. 5-41. A retrogressive wave winding, two coils per slot.

Figures 5-38; 5-39; 5-40; 5-41

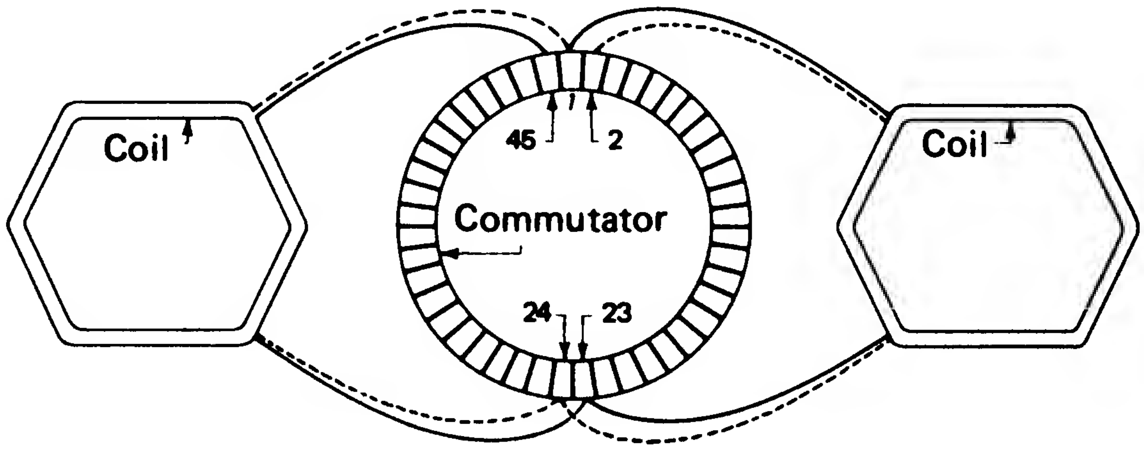


Fig. 5-42. A retrogressive wave winding.

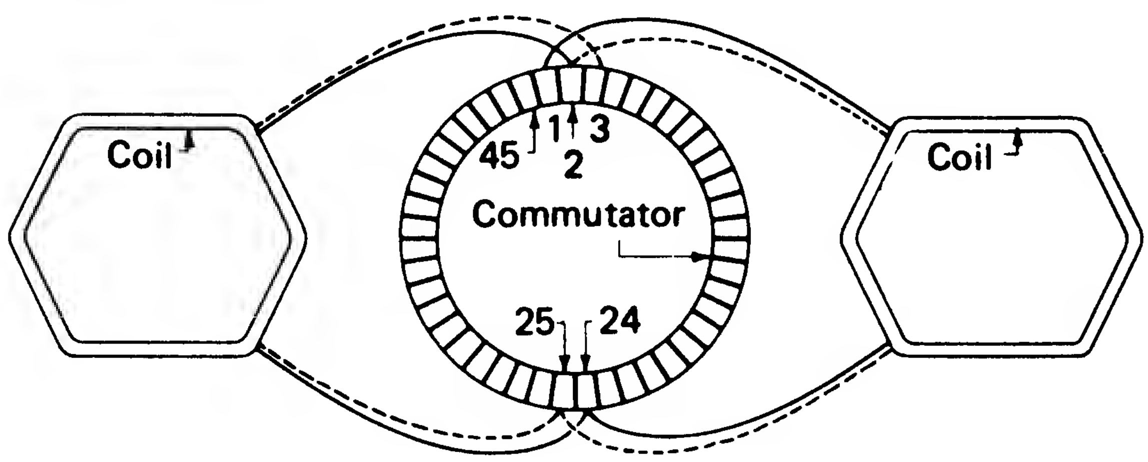


Fig. 5-43a. A progressive wave winding.

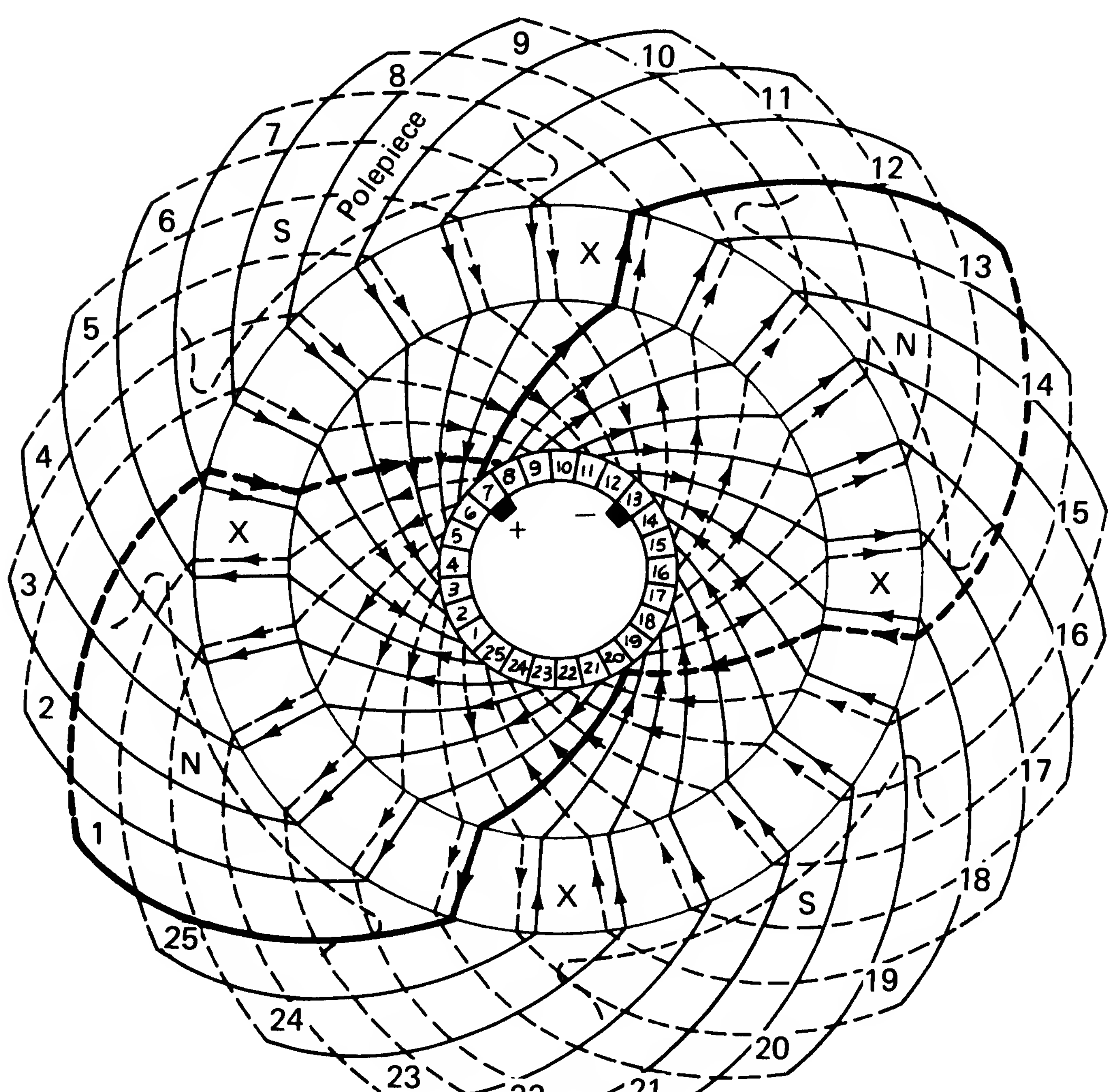


Fig. 5-43b. A circular diagram of a four-pole, wave-wound armature.

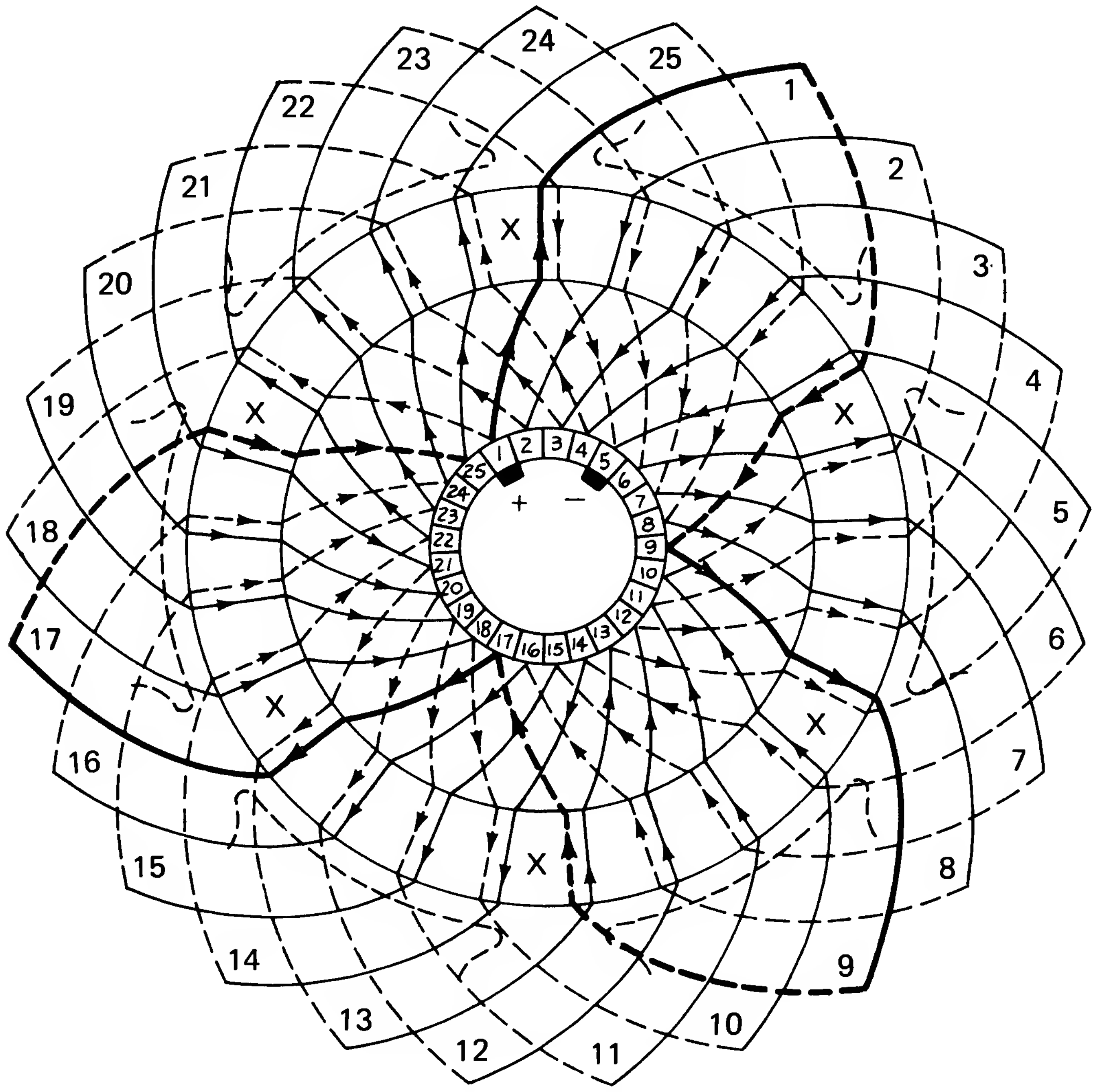


Fig. 5-43c. A circular diagram of a six-pole, wave-wound armature.

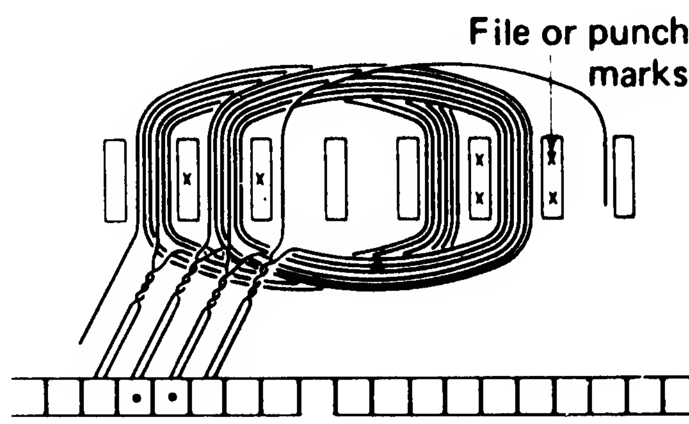


Fig. 5-44. Pitch and lead data of a lap winding may be marked on the armature.

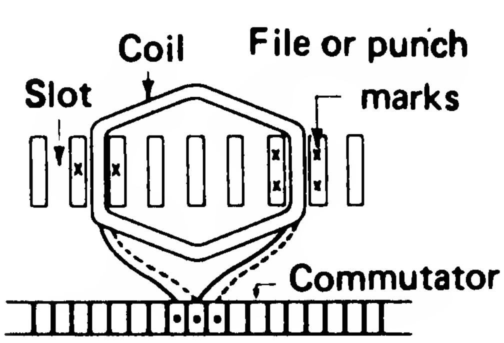


Fig. 5-45. Pitch and lead data of a lap winding marked at the slots and bars of one particular coil.

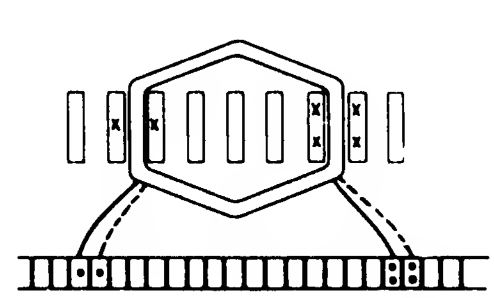


Fig. 5-46. Pitch and lead data of a wave winding marked at the slots and bars of a particular coil.

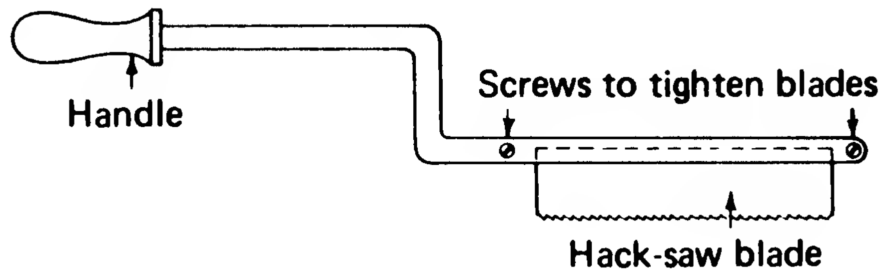


Fig. 5-47. A tool for cutting slots in commutator bars.

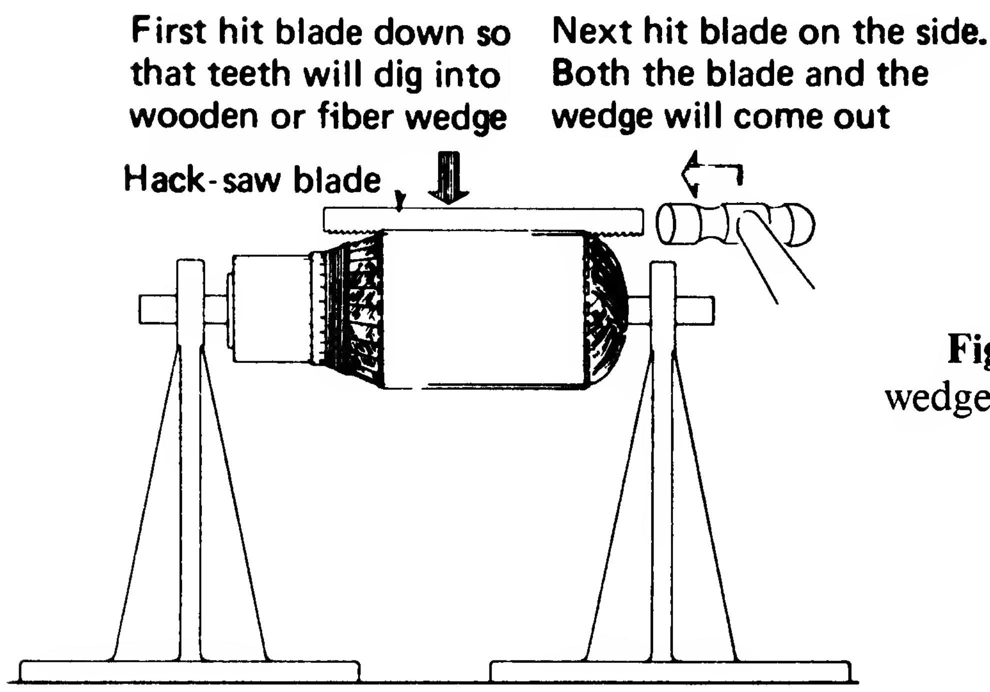
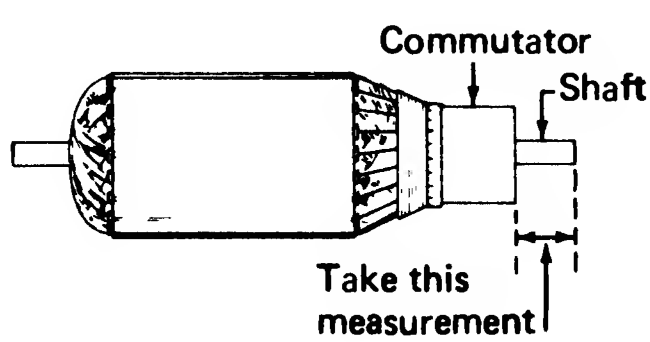


Fig. 5-48. Method of removing wedges from armature or stator slots.

Fig. 5-49. Measurements to be taken before removing commutator.



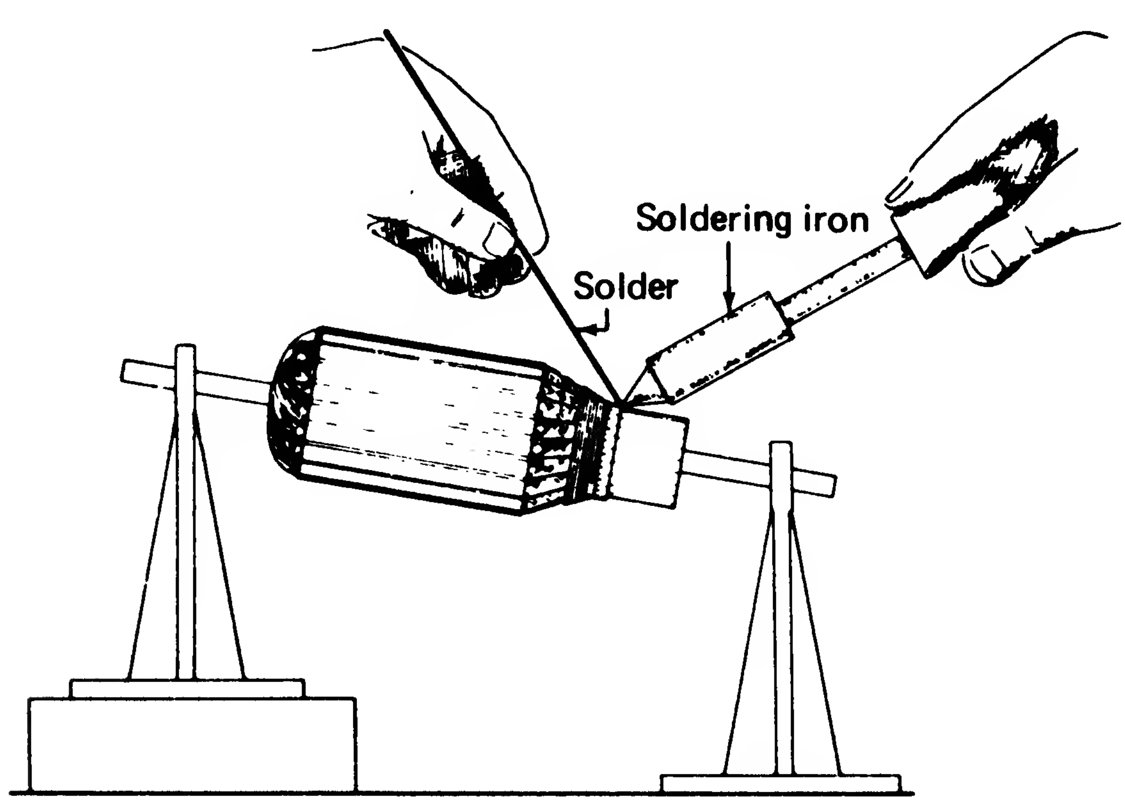


Fig. 5-50. Soldering leads to the commutator. The soldering iron is held slightly above the horizontal.

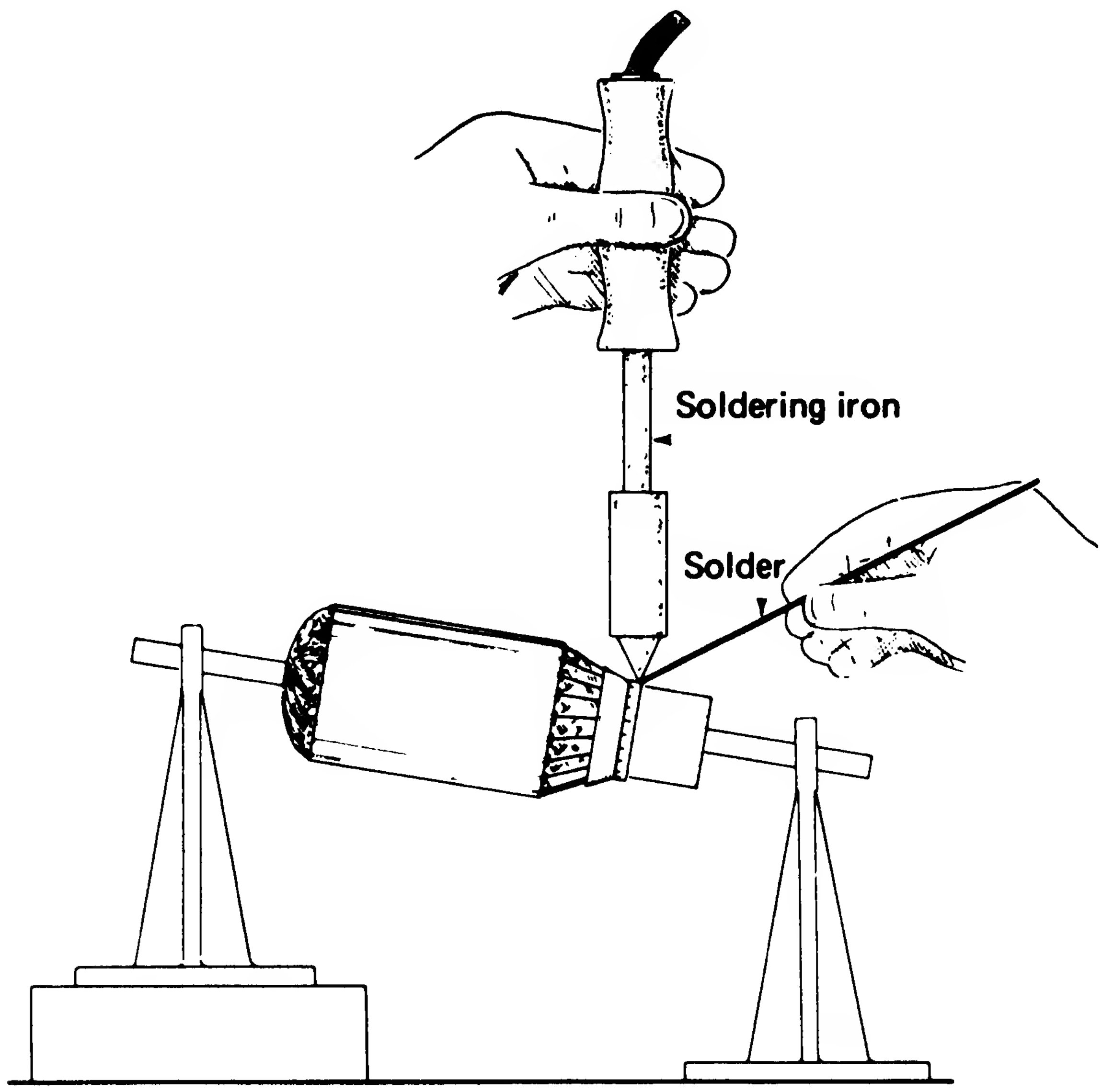


Fig. 5-51. Holding the iron vertically prevents the solder from spanning two bars.

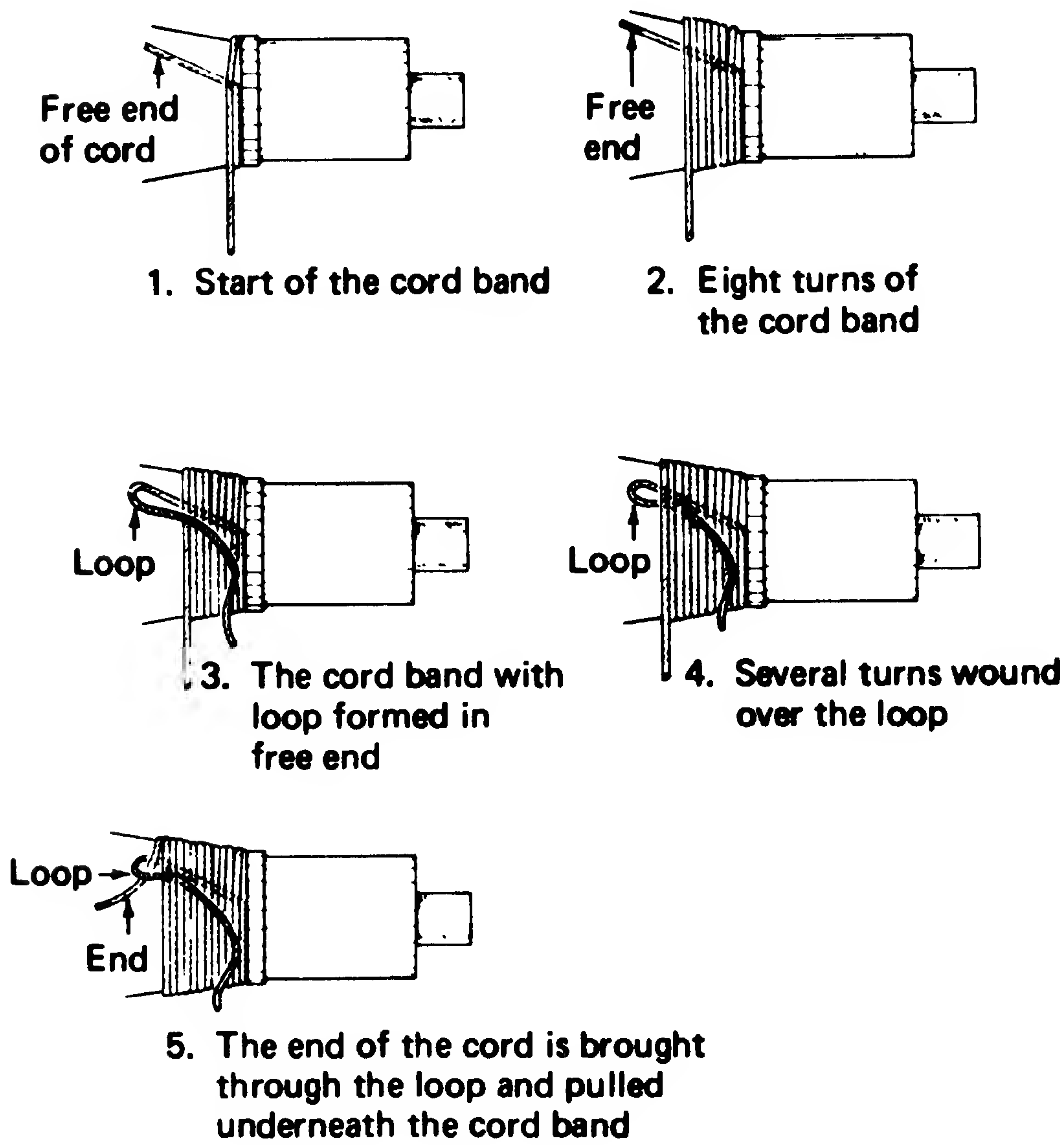


Fig. 5-52. A method of winding a cord band on an armature.

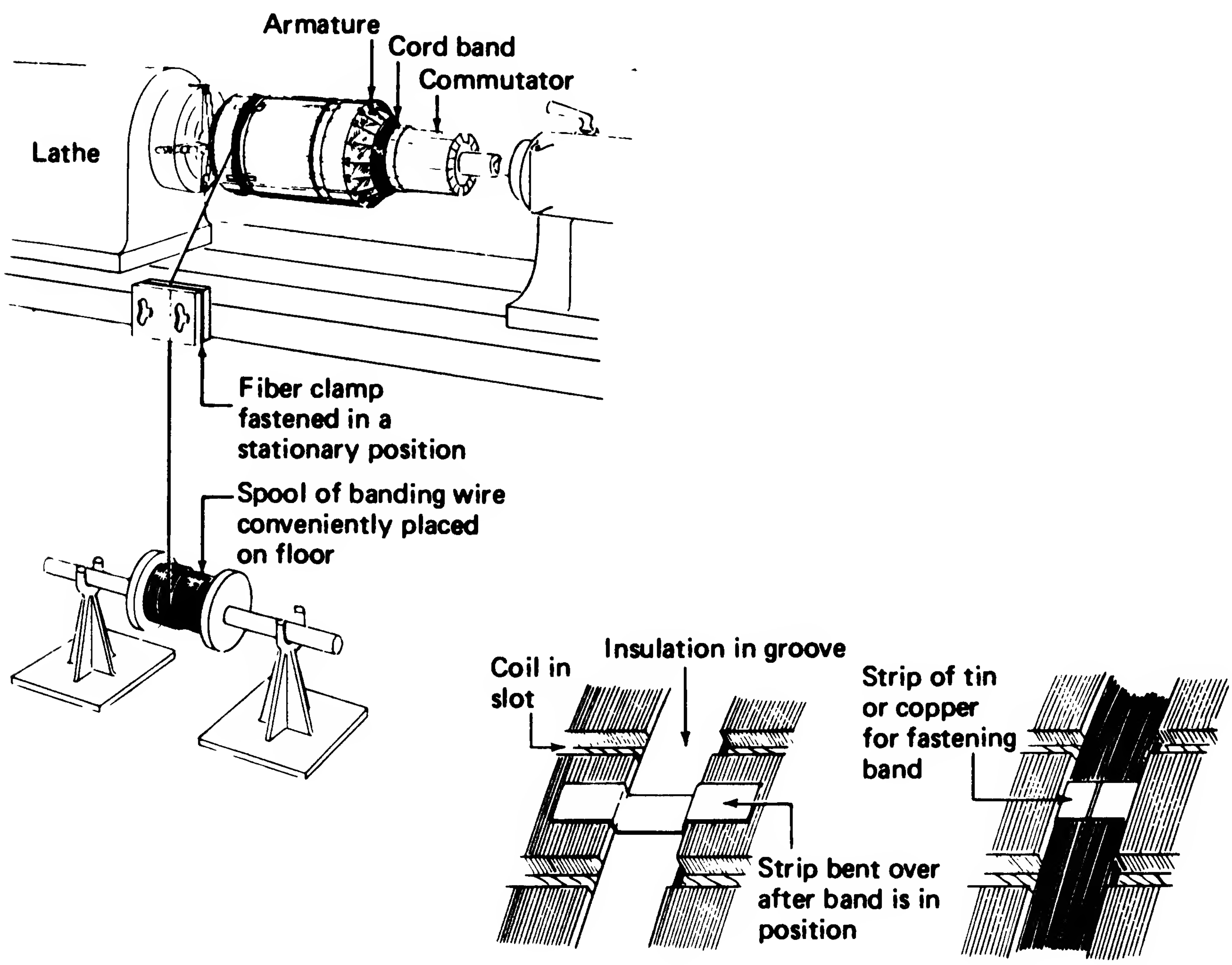


Fig. 5-53. A method of banding an armature with steel wire.

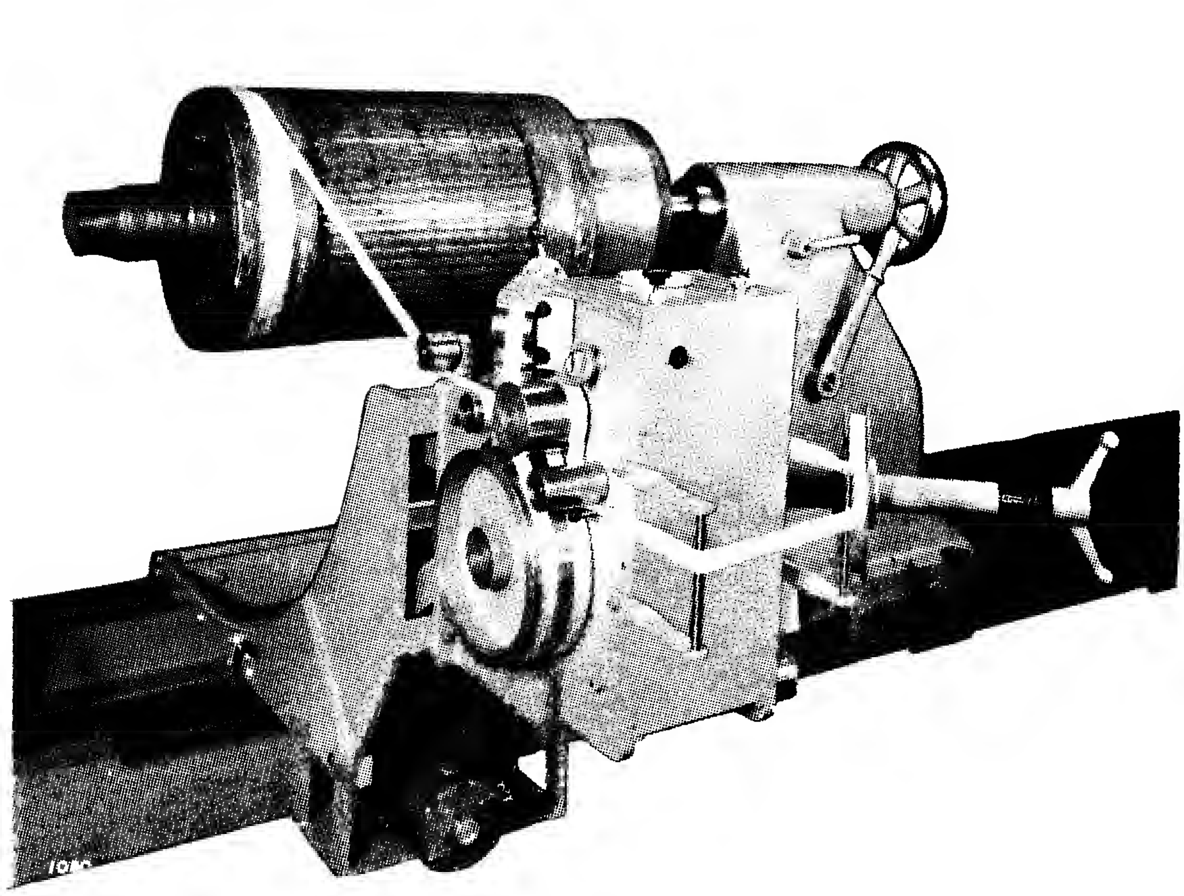


Fig. 5-54. Peerless glass tape tension device. (*Peerless Tool Division Cam Industries Inc.*)

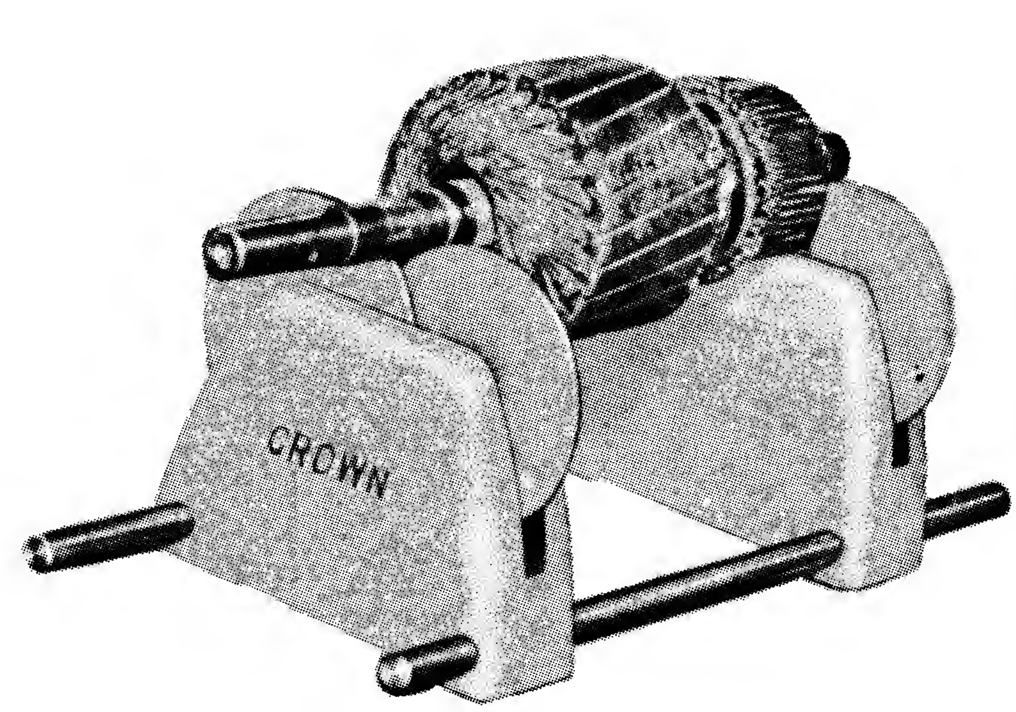


Fig. 5-55. Armature mounted on balancing ways. (*Crown Industrial Products*)

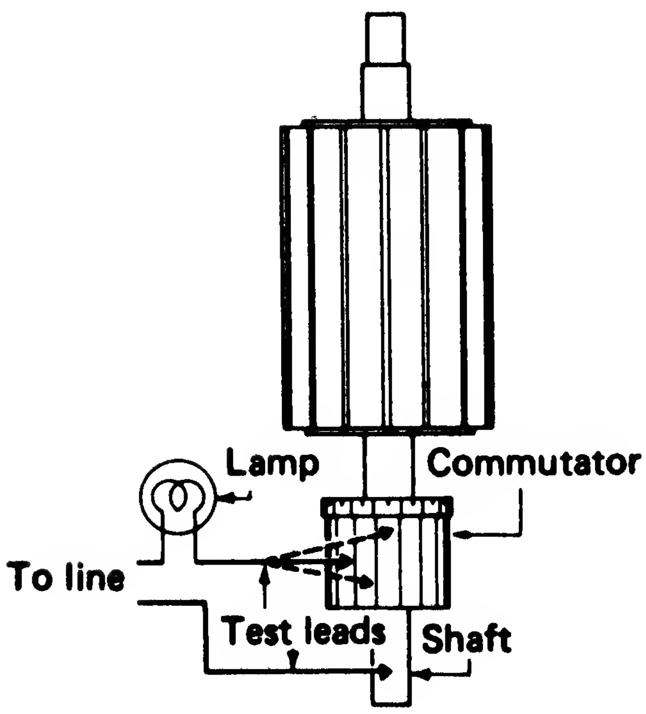
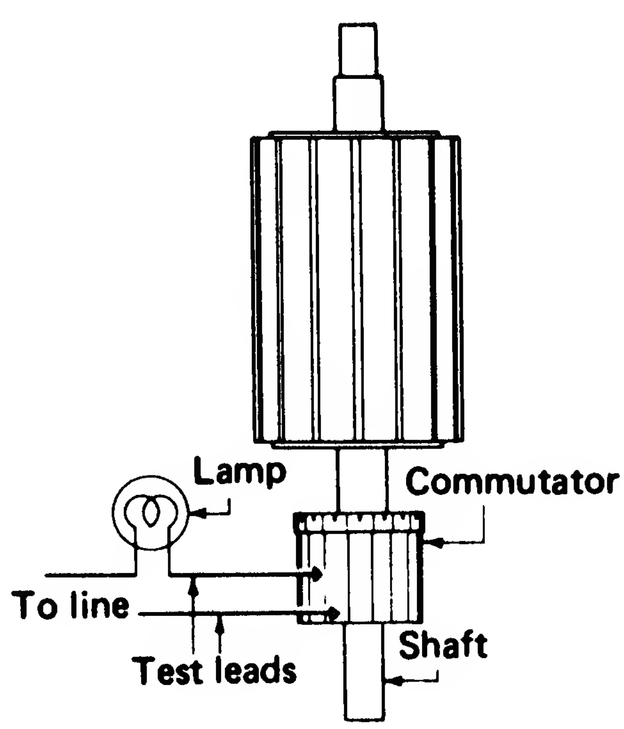


Fig. 5-56. A test for a grounded commutator.

Fig. 5-57. A test circuit for finding shorts between bars.



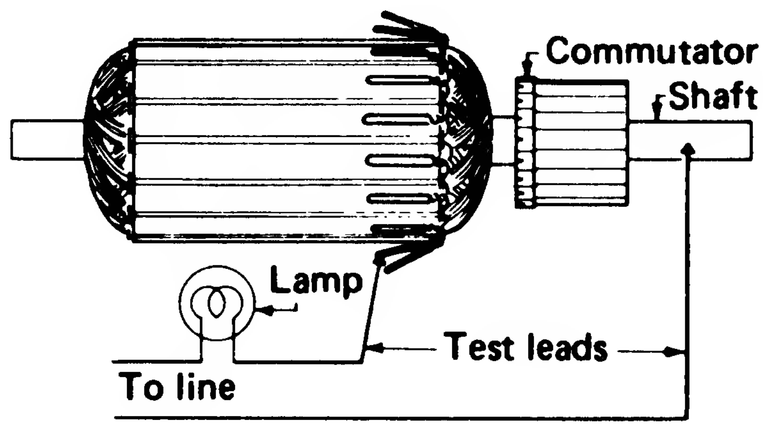


Fig. 5-58. Testing the winding for grounds before the leads have been connected to the commutator.

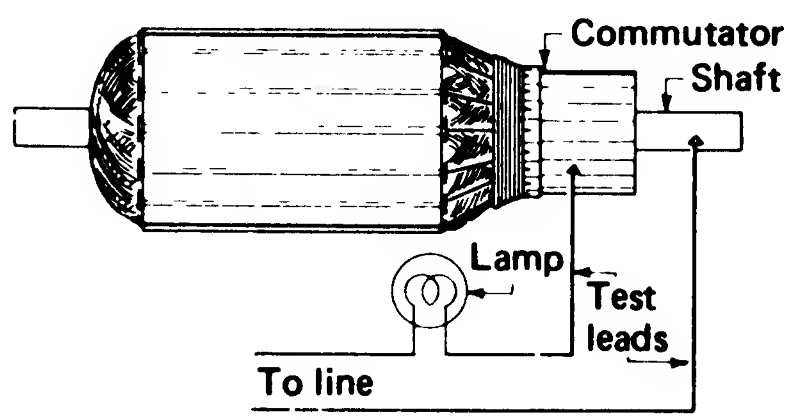


Fig. 5-59. Testing the completed armature for grounds after the leads have been connected to the commutator.

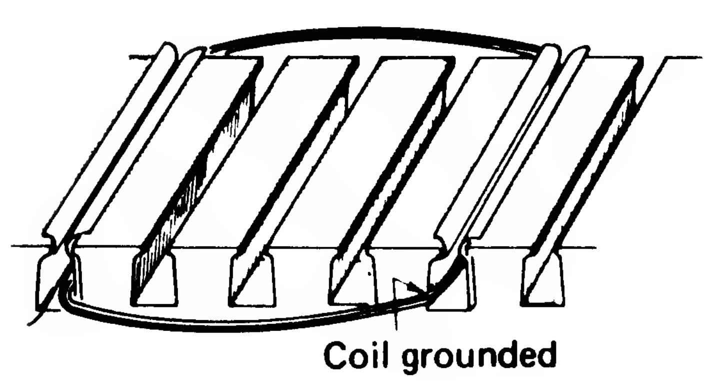


Fig. 5-60. The coil may contact the iron core due to torn or improperly cut slot insulation.

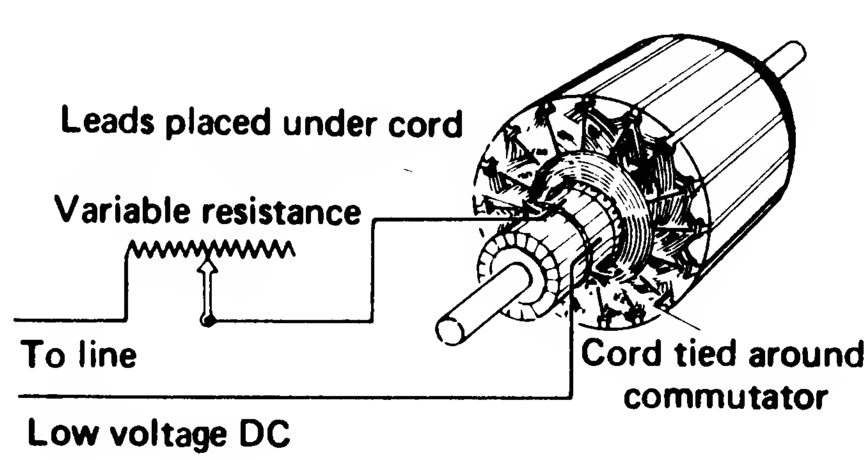
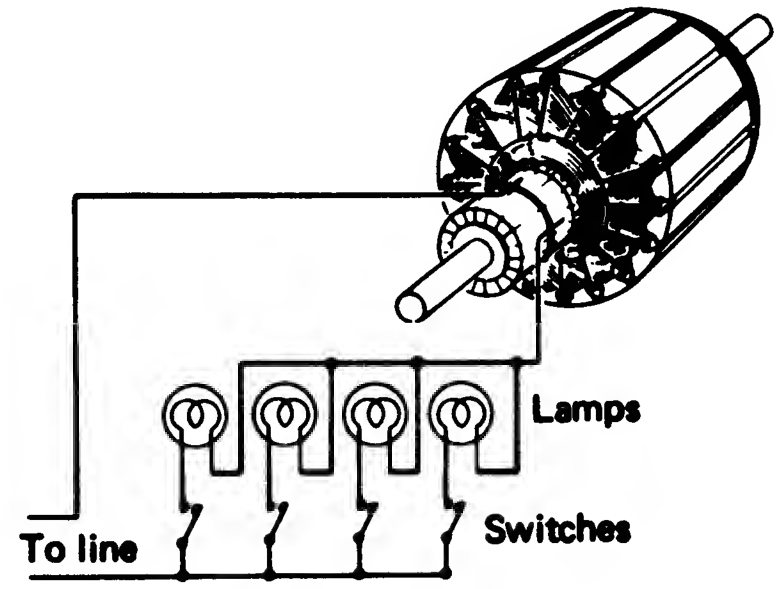


Fig. 5-61. A variable resistance is placed in series with the line in order to obtain a normal deflection on the meter.

Fig. 5-62. Lamps placed in series with 115 volts of direct current to supply current to the armature for testing. Switches *1, 2, 3,* and *4* may be connected in the circuit, depending on the armature tested and the amount of current necessary.



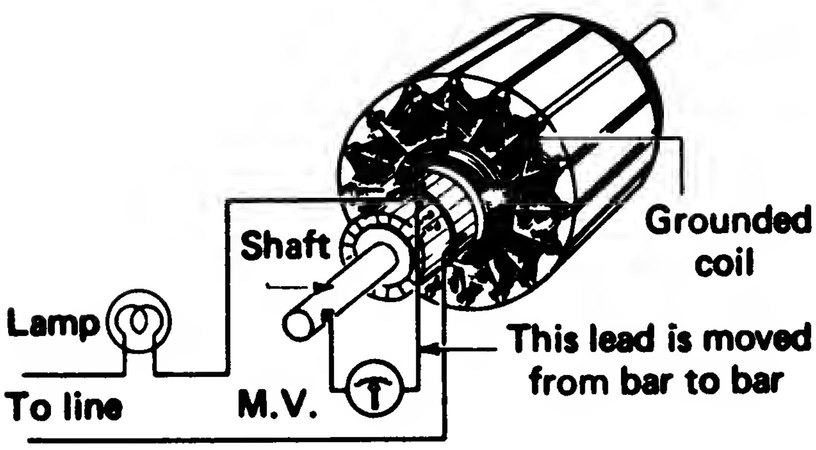


Fig. 5-63. Testing an armature for grounds. One meter lead is moved from bar to bar until the lowest reading is indicated on the meter. The grounded coil is connected to this bar.

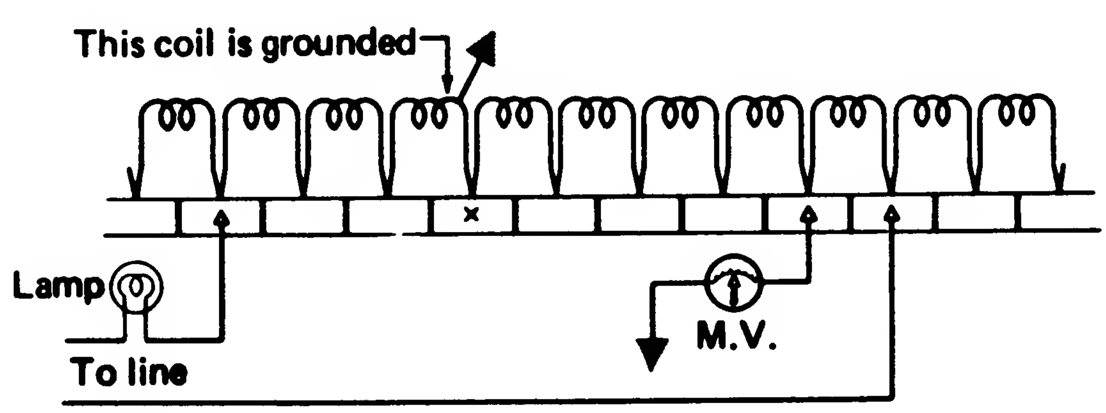
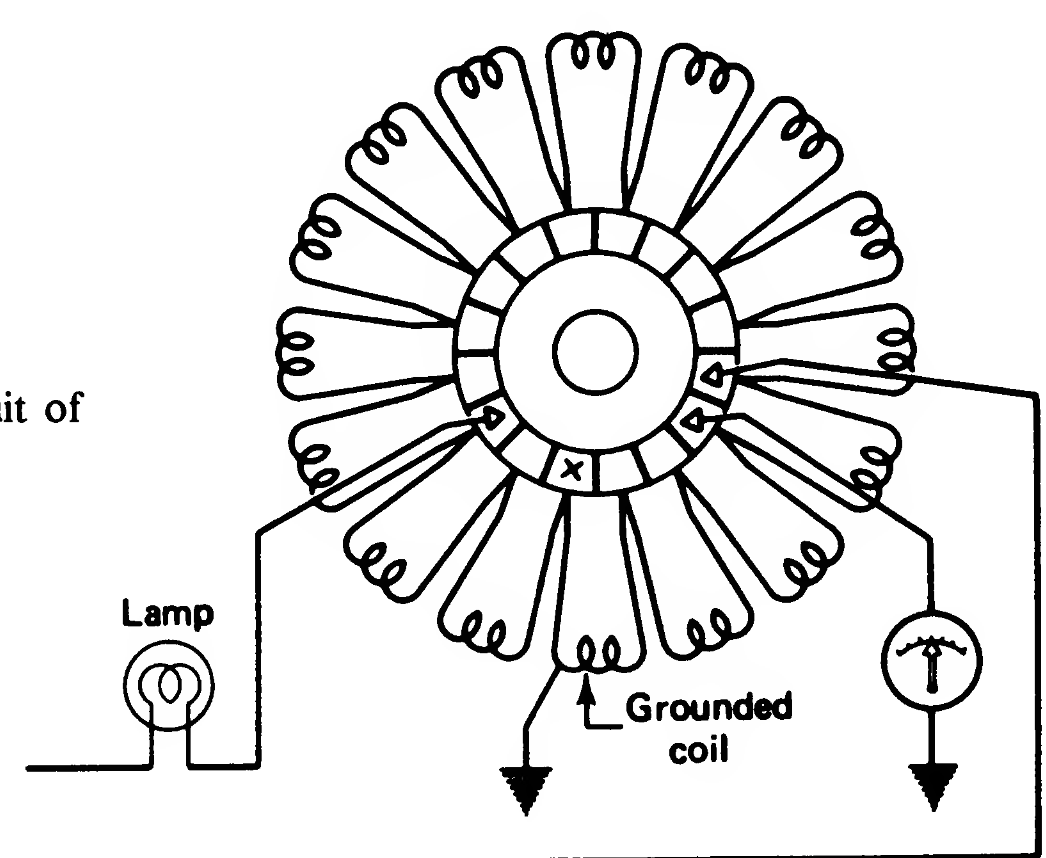


Fig. 5-64. A schematic diagram of the test circuit shown in **Fig. 5-63.**

Fig. 5-65. A complete circuit of ground test.



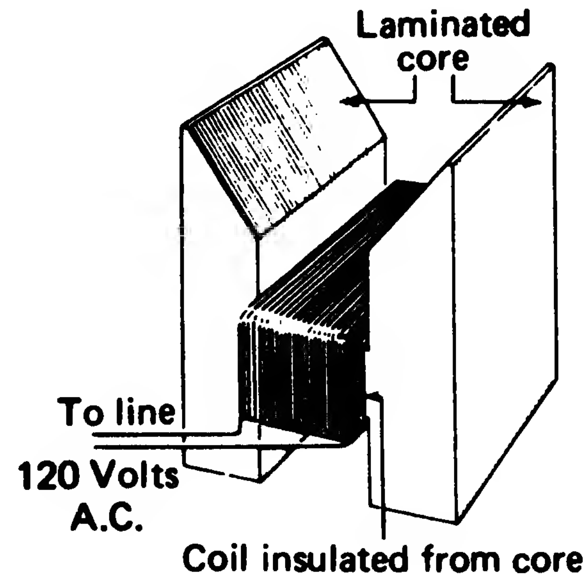


Fig. 5–66. A growler consisting of a laminated core on which a coil of wire is wound.

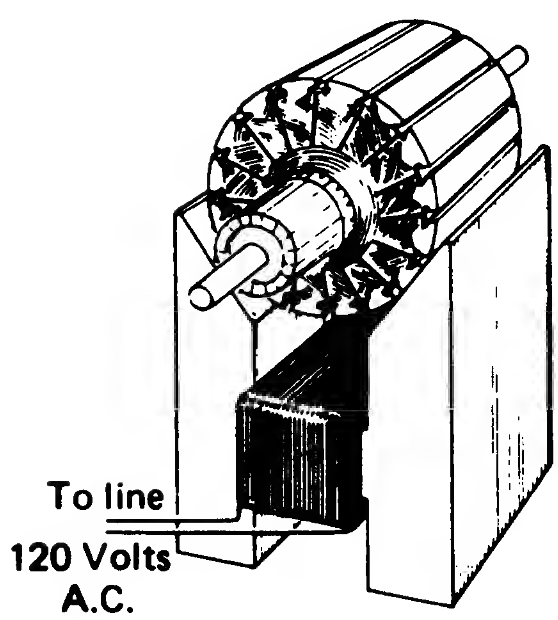


Fig. 5–67. An armature in position on a growler for test purposes.

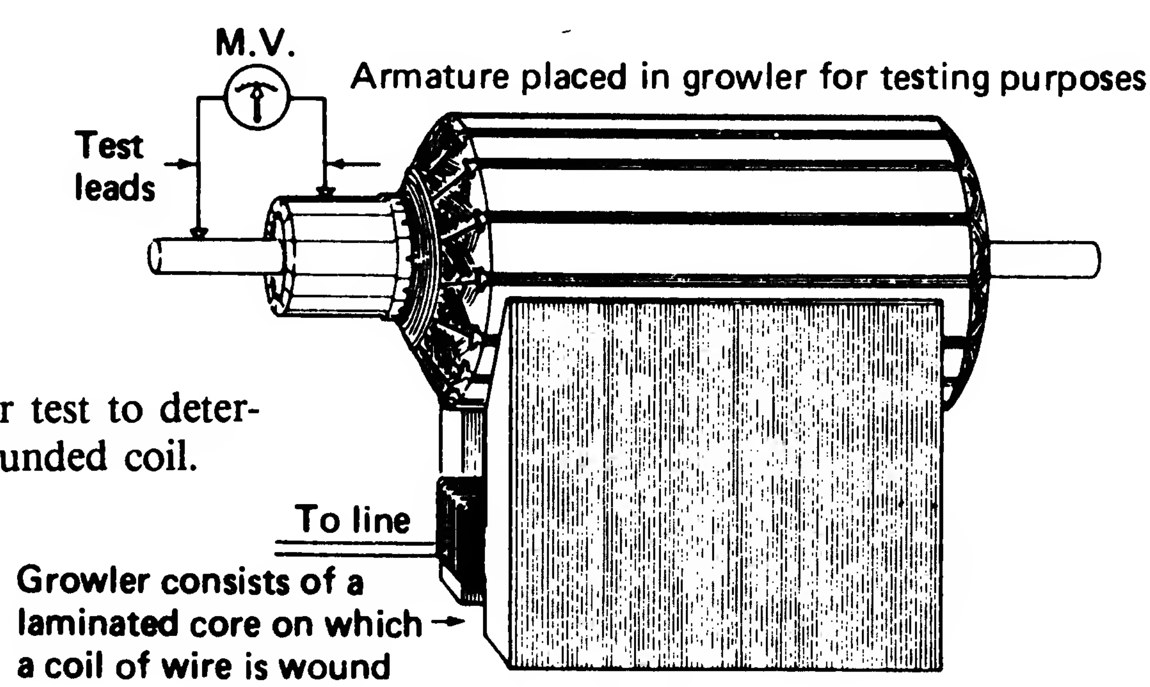


Fig. 5–68. The growler test to determine the location of a grounded coil.

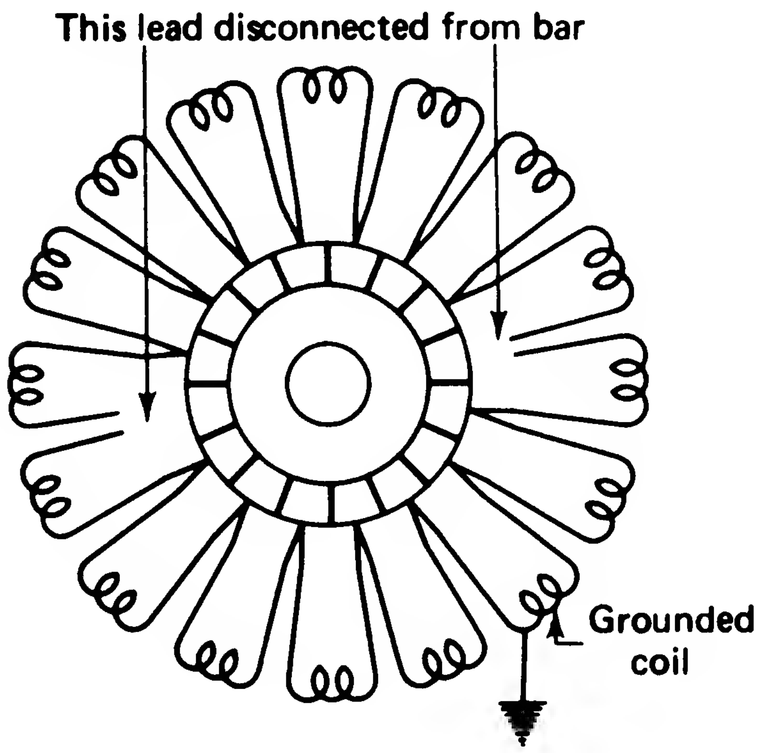


Fig. 5-69. Locating a grounded coil by the trial method. The leads are disconnected on opposite sides of the commutator, and in this case, the bottom half of the armature will test grounded.

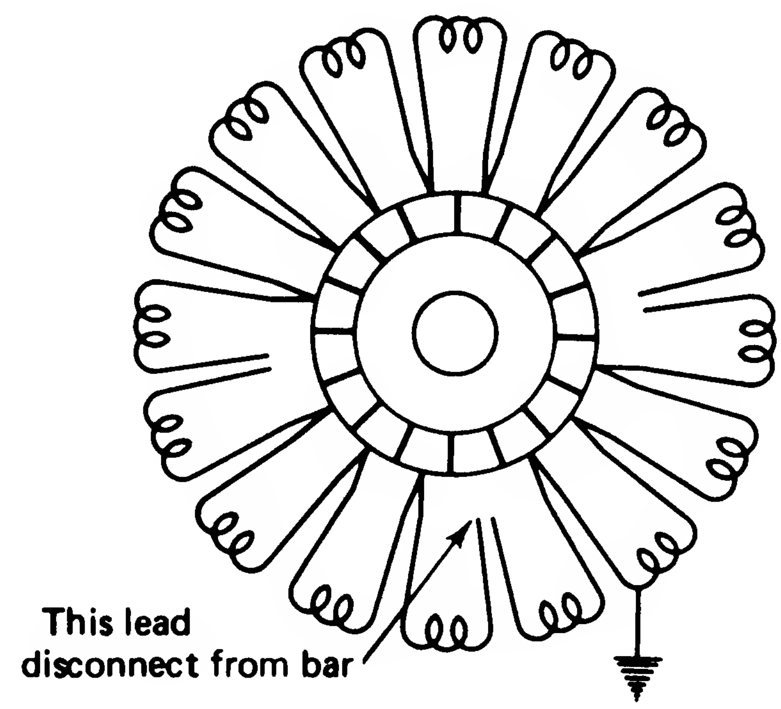


Fig. 5-70. Disconnect a lead in the center of the grounded group and test in which quarter grounded coil is located.

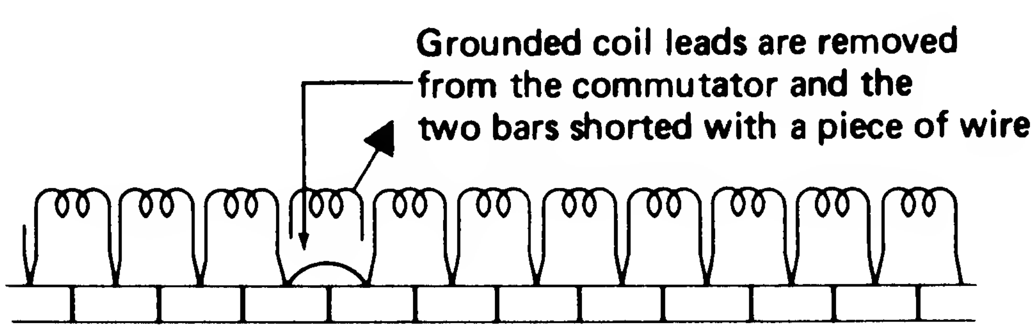


Fig. 5-71. Schematic diagram showing how a grounded coil is disconnected from the commutator.

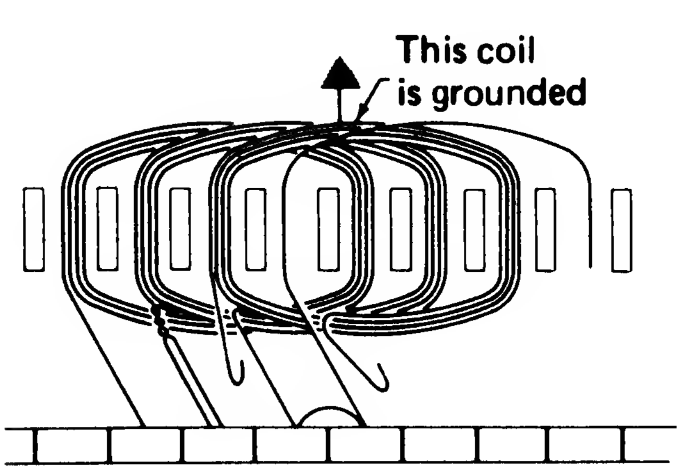


Fig. 5-72. Disconnecting a grounded coil from a loop winding.

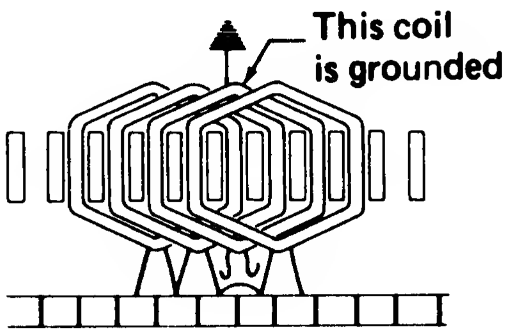


Fig. 5-73. Disconnecting a grounded coil from a lap winding.

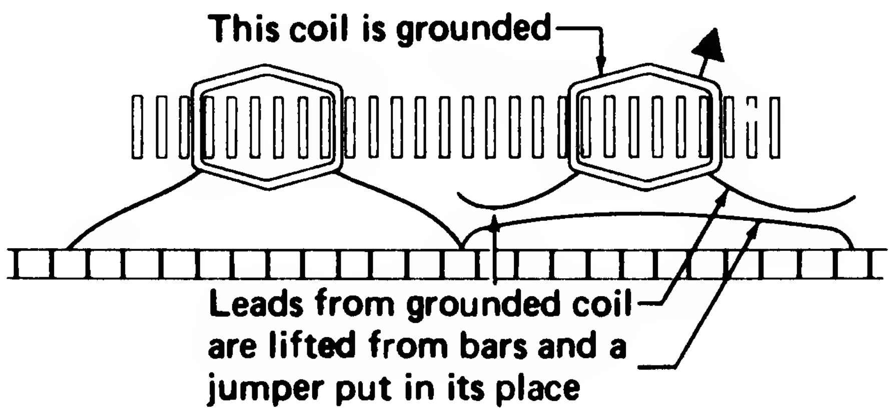
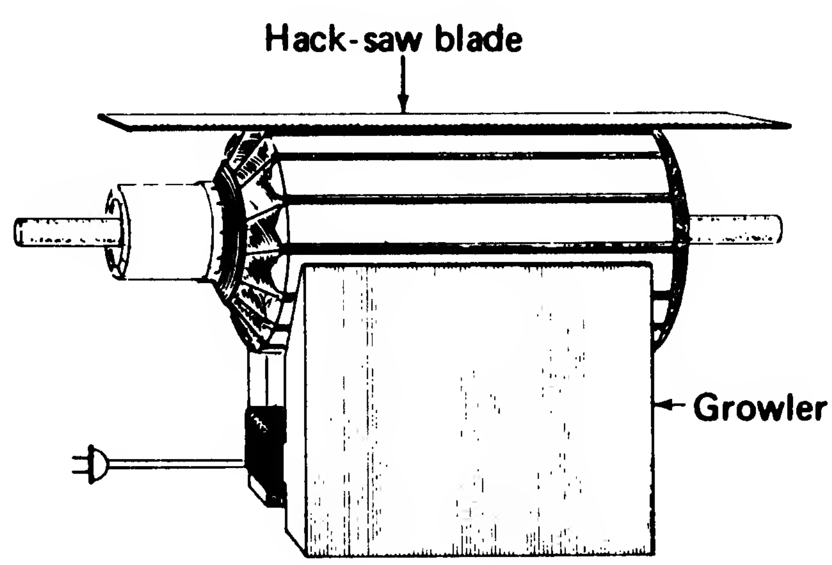


Fig. 5-74. Disconnecting a grounded coil from a wave winding.

Fig. 5-75. Testing an armature for shorts by placing a hack-saw blade over the top slot.



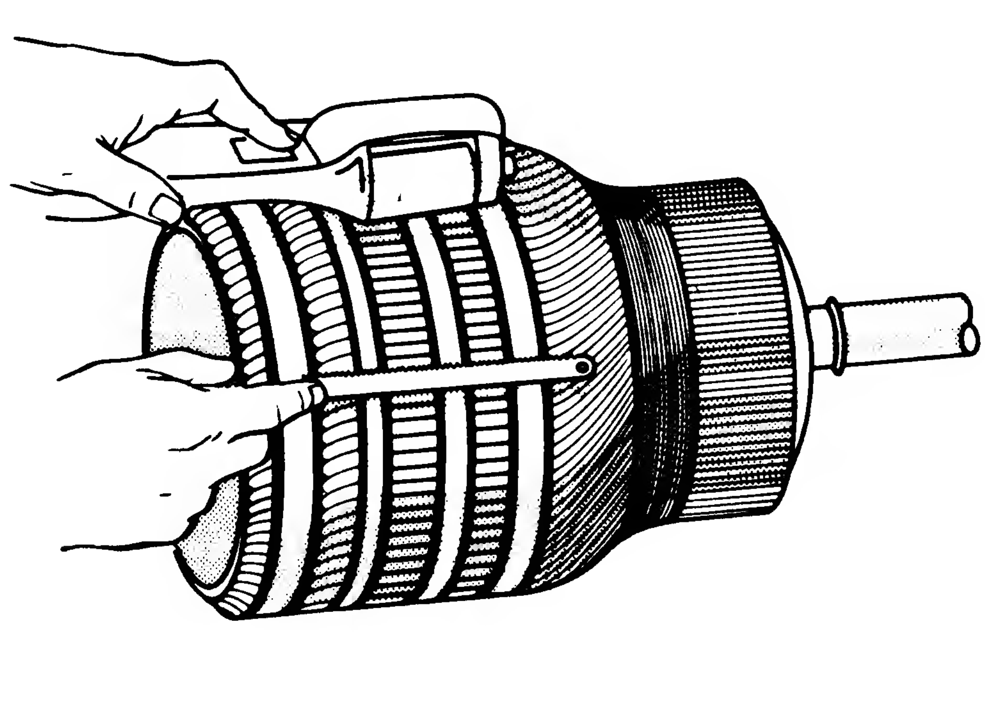
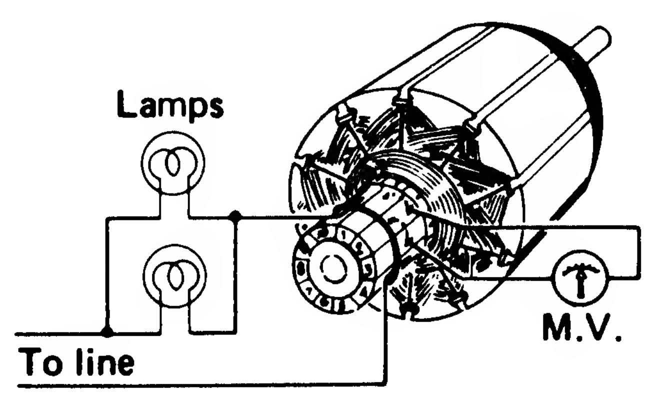


Fig. 5-76. Using an internal growler to locate shorted coils in an armature.

Fig. 5-77. An external growler. This is used for testing armatures for shorts, opens and grounds. (*Crown Industrial Products*)

Fig. 5-78. Testing an armature for shorted coils by using the bar-to-bar test. A shorted coil will be indicated by a low or zero reading on the meter.



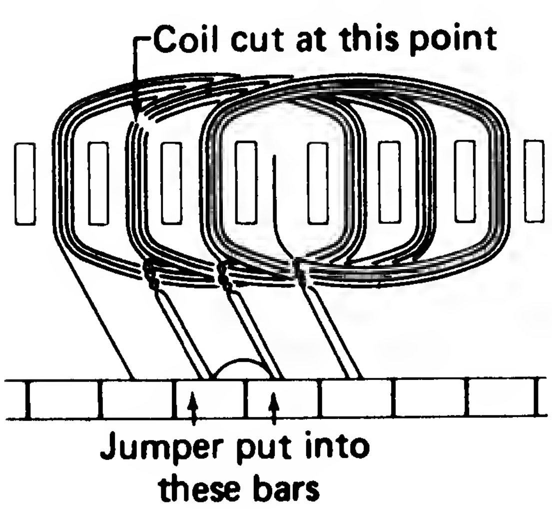
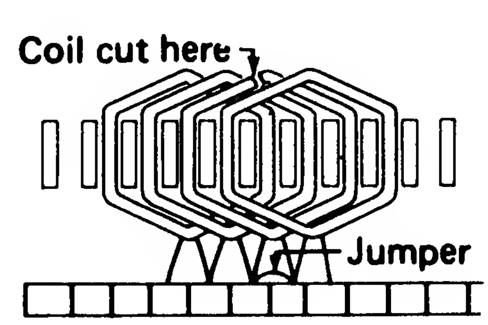


Fig. 5-79. Cutting the shorted coil and connecting a jumper between the two bars connected to the coil.

Fig. 5-80. Cutting out a shorted coil on a form-wound armature.



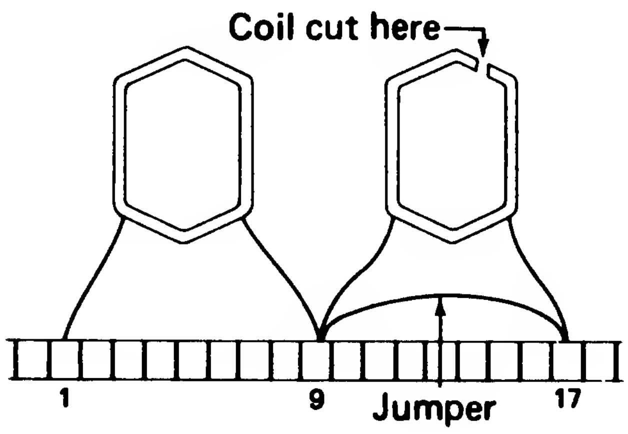


Fig. 5-81. Cutting out a shorted coil on a four-pole wave winding.

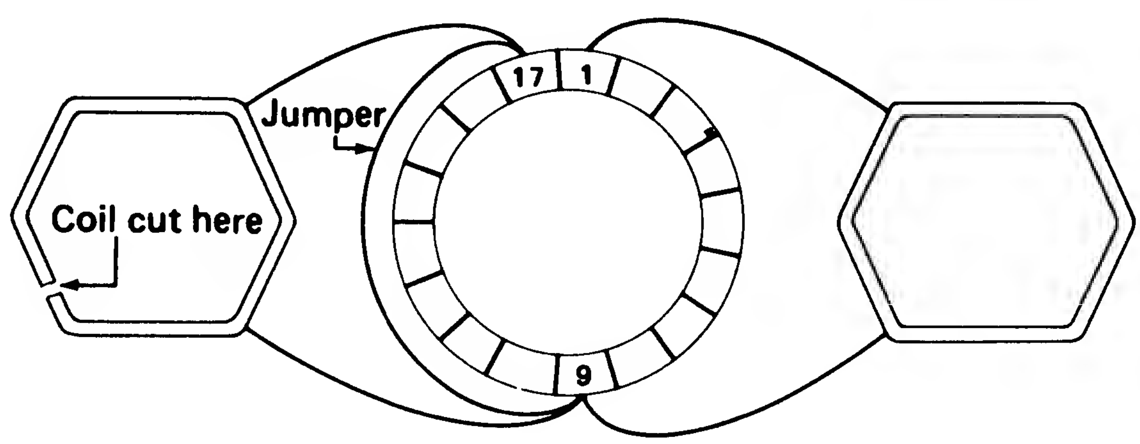


Fig. 5-82. Cutting out a shorted coil on a wave winding.

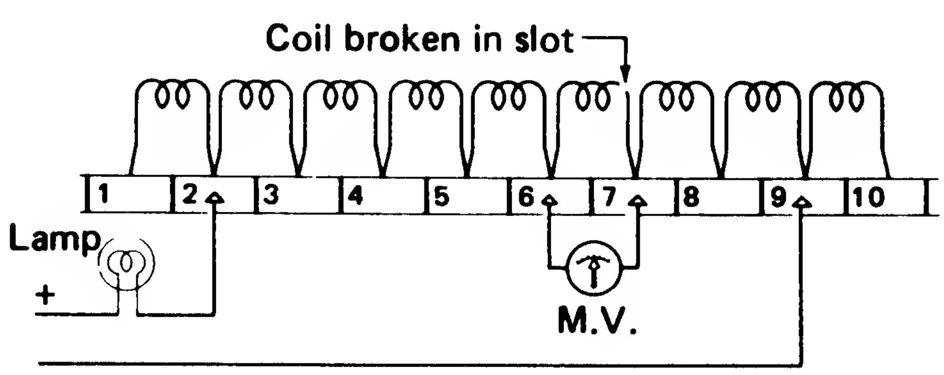
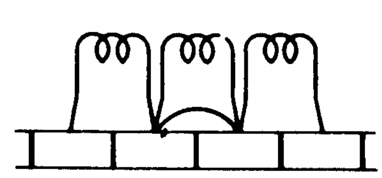


Fig. 5-83. A method of locating an open coil. The meter will not show a reading until it bridges bars 6 and 7. The meter completes the circuit from positive to negative.

Fig. 5-84. A method of jumping out an open coil on a lap winding.



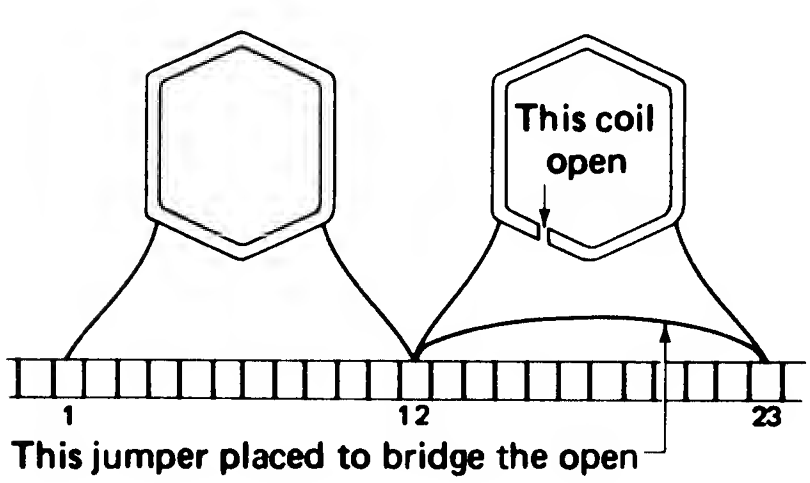


Fig. 5-85. A method of repairing a wave-wound armature having an open coil.

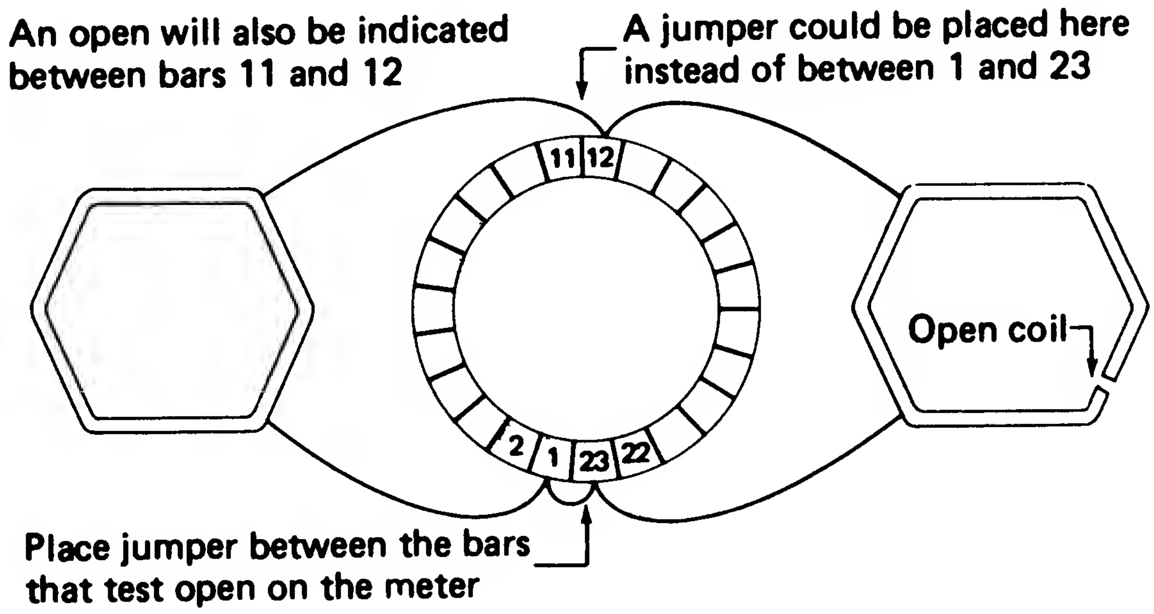


Fig. 5-86. A quick method of closing an open on a four-pole wave winding.

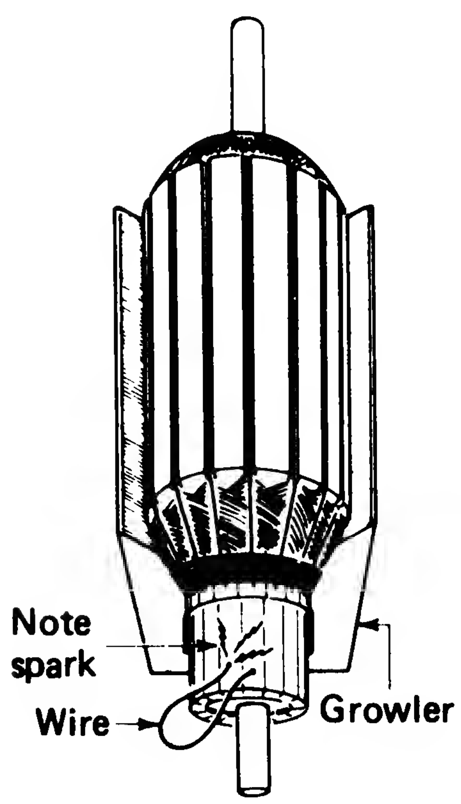
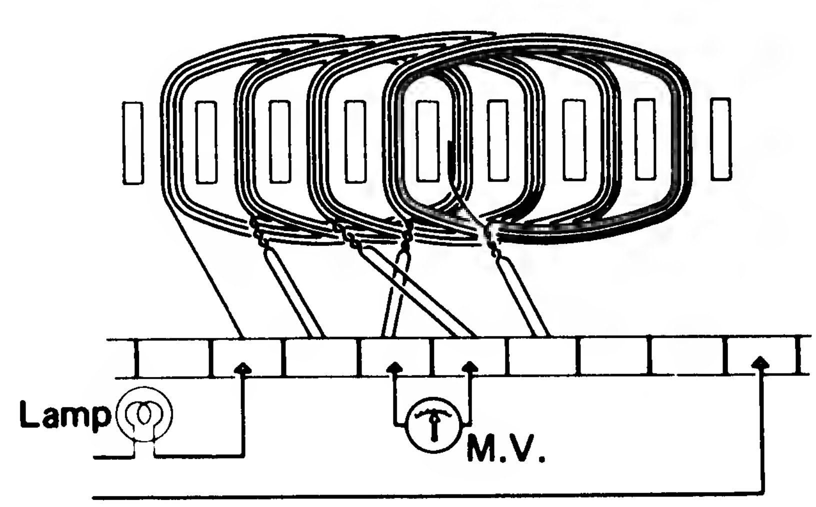


Fig. 5-87. If two bars are shorted with a piece of wire, a small spark indicates a complete circuit through the coil.

Fig. 5-88. Loops placed in wrong bars.



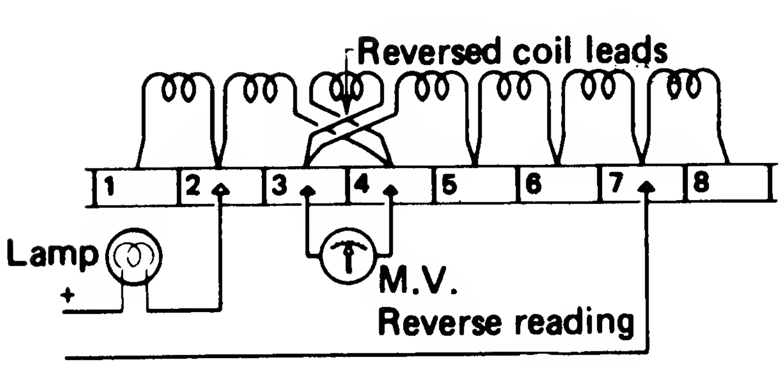


Fig. 5-89. A test of a loop winding for reversed coils. Between bars 3 and 4 the meter will indicate a reversed reading; between bars 2 and 3 a double reading; between bars 4 and 5 a double reading. All others will be normal.

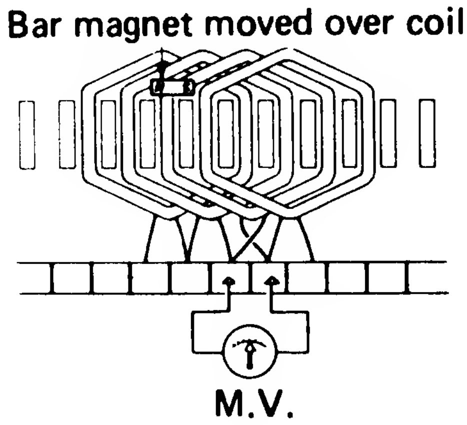
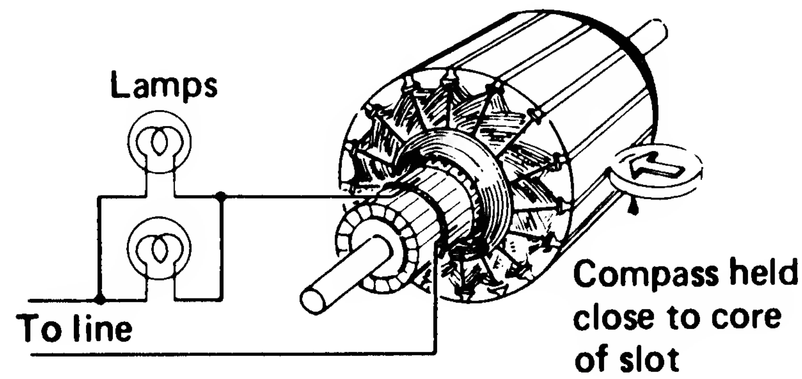


Fig. 5-90. A method of testing for reversed coils by running a bar magnet over each coil and noting the meter needle. When the reversed coil is reached, the needle will reverse.

Fig. 5-91. Test for a reversed coil by using a compass. The armature is turned slowly until the reversed coil is alongside the compass. The needle will reverse at this point.



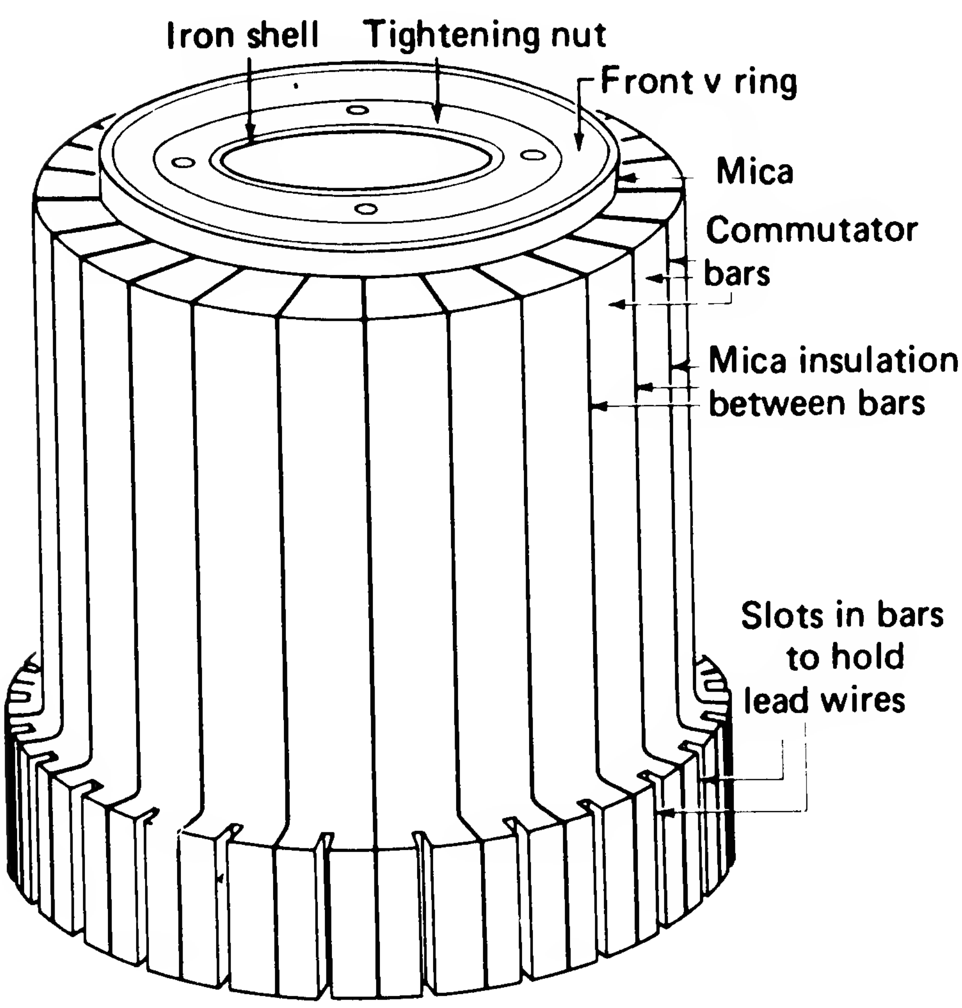
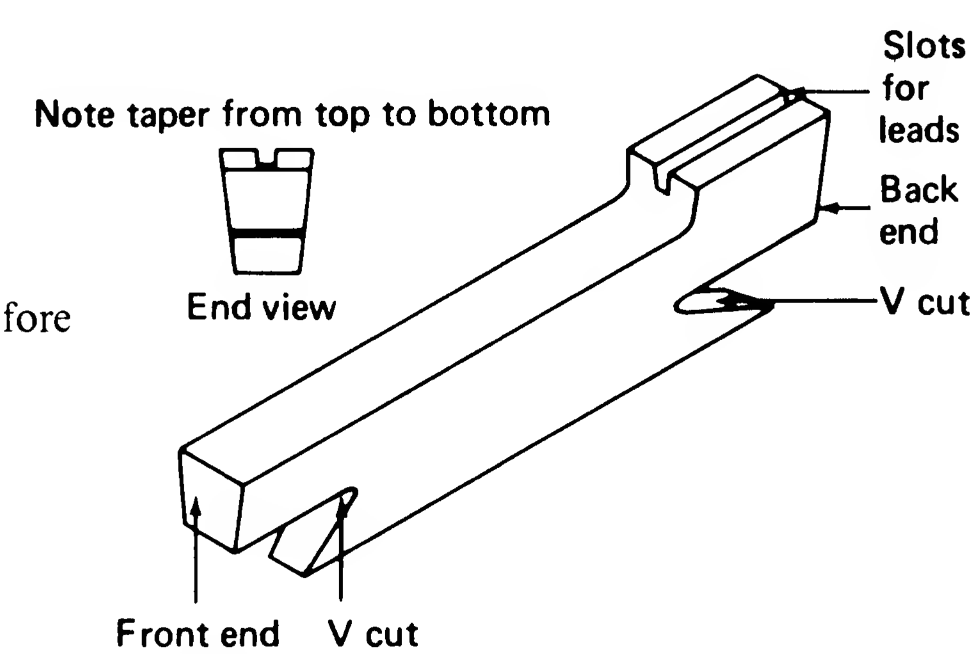


Fig. 5-92. A typical commutator.

Fig. 5-93. A commutator bar before it is mounted.



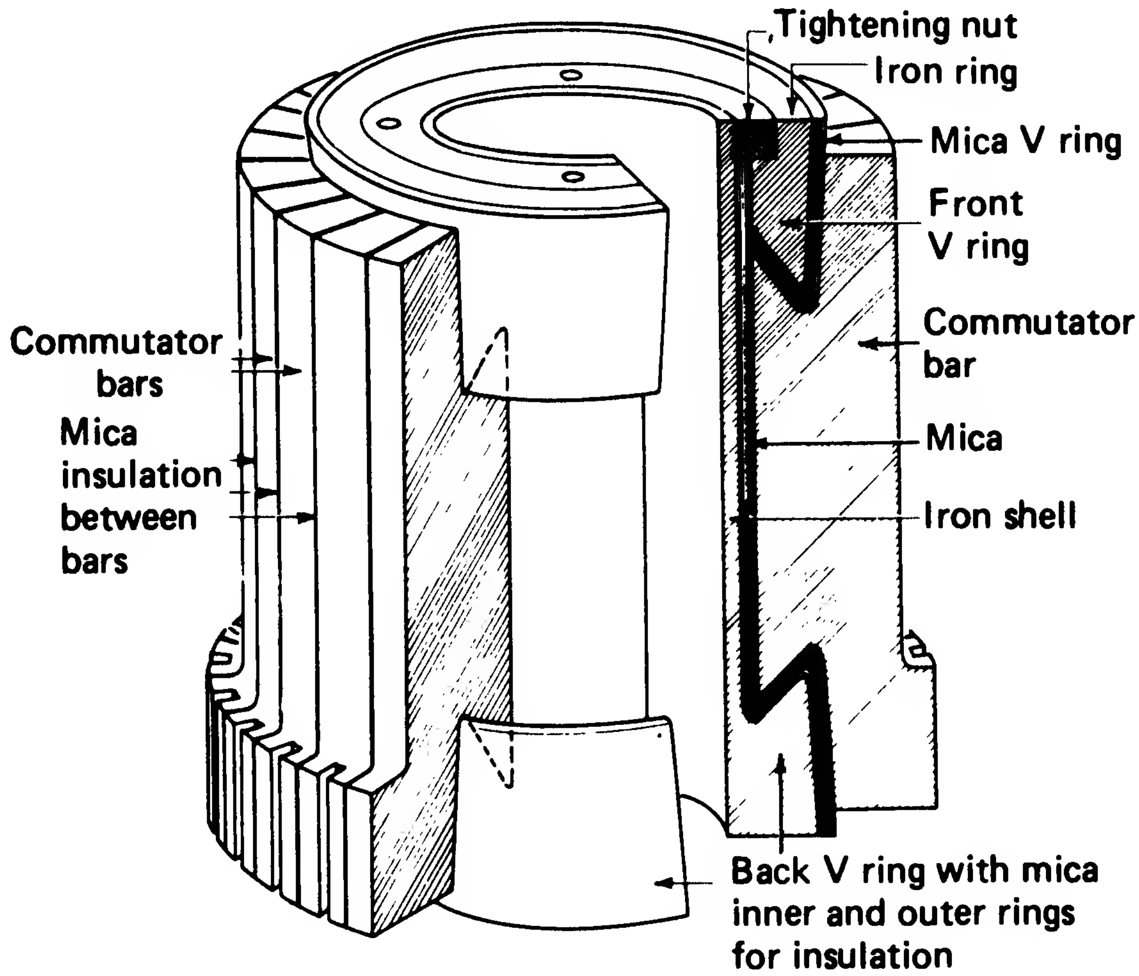


Fig. 5-94. A commutator with a portion removed to show section and assembly.

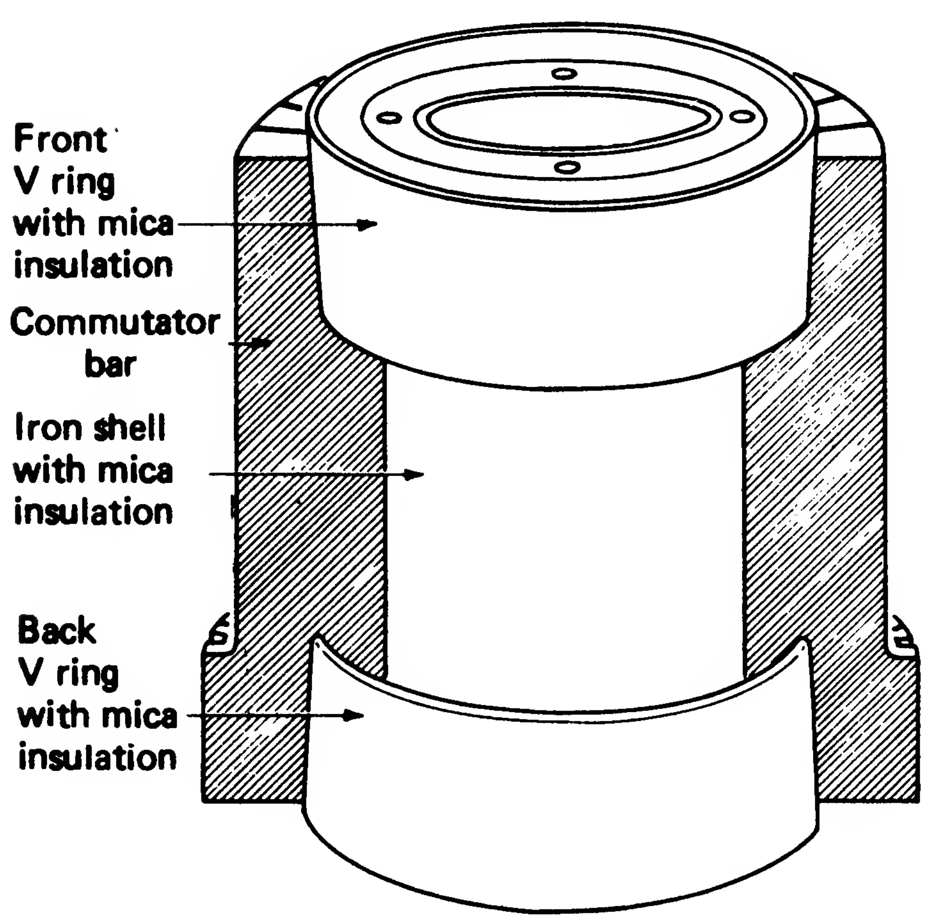


Fig. 5-95. A commutator with half the bars removed and the front and back V ring in place.

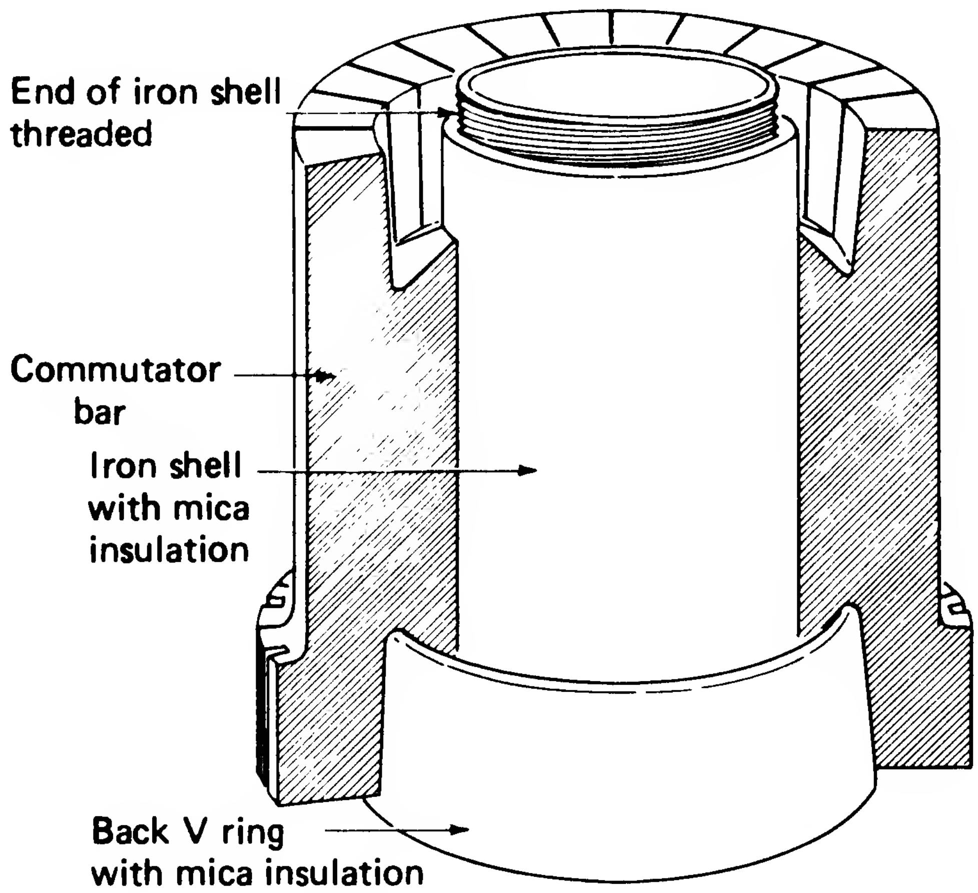


Fig. 5-96. A commutator with the front V ring and half the bars removed.

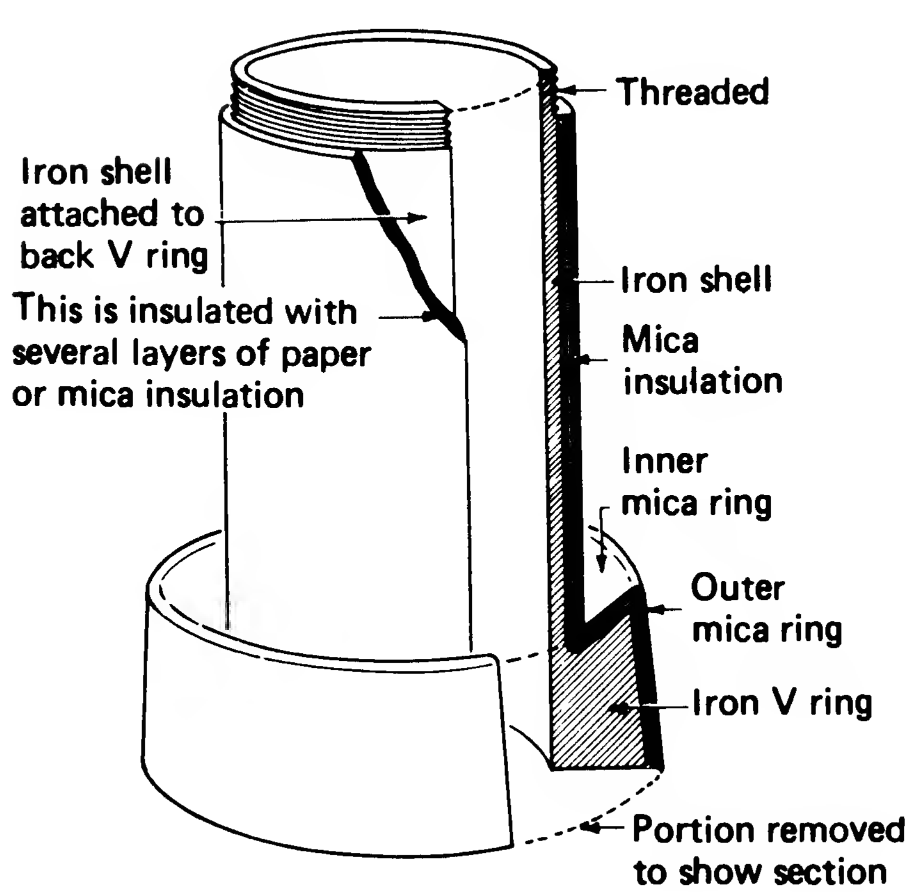
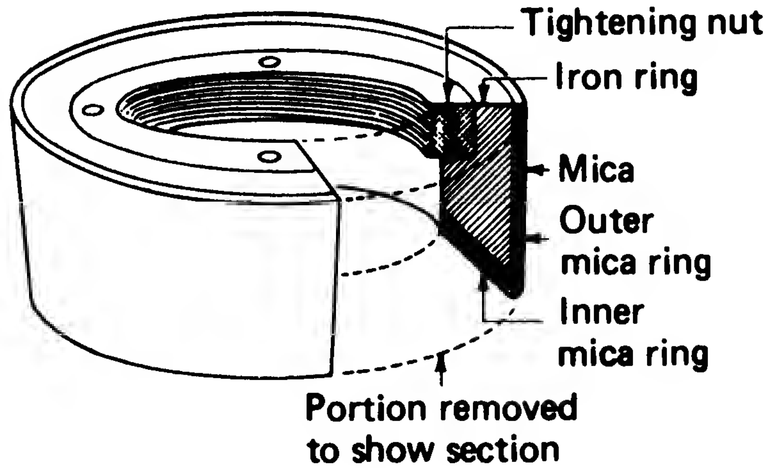


Fig. 5-97. A back V ring with shell attached to iron core.



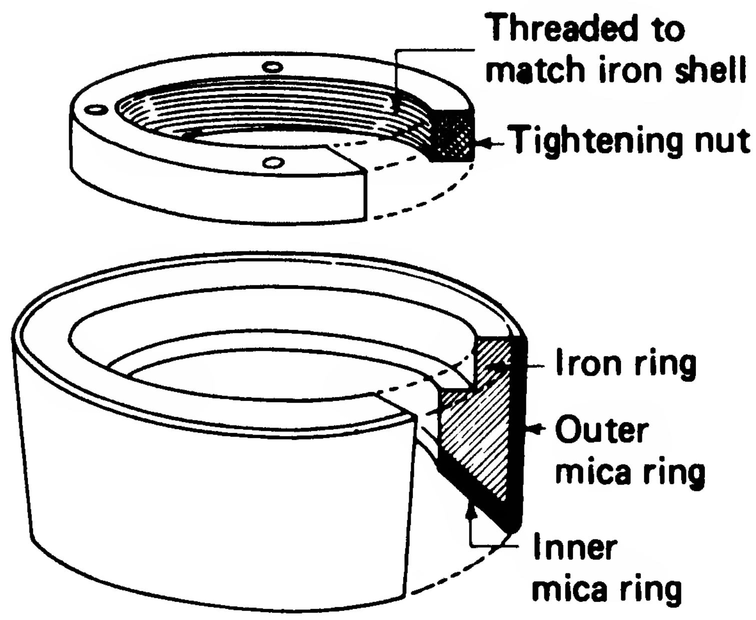


Fig. 5-98. A front V ring and tightening nut.

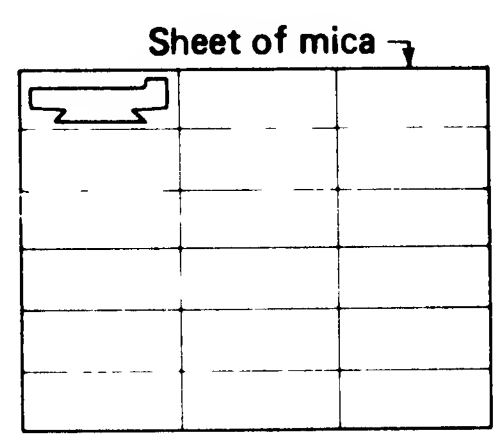


Fig. 5-99. The mica sheet marked off into small strips of mica.

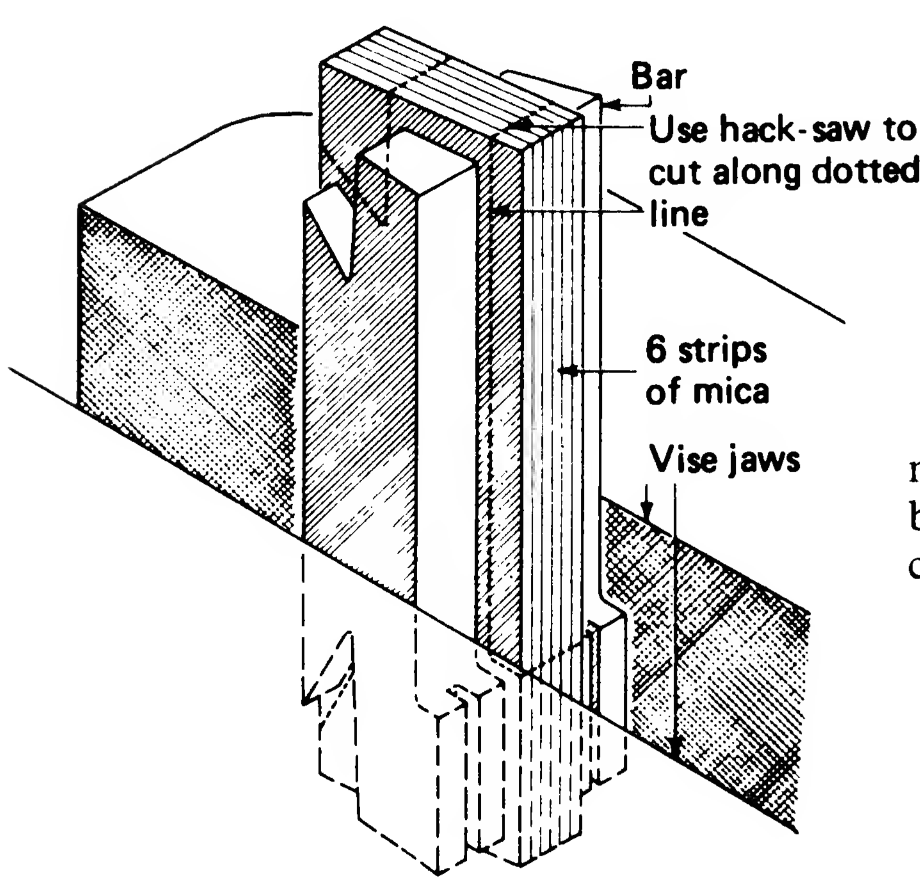


Fig. 5-100. Rectangular strips of mica stacked between two commutator bars and placed in a vise before being cut.

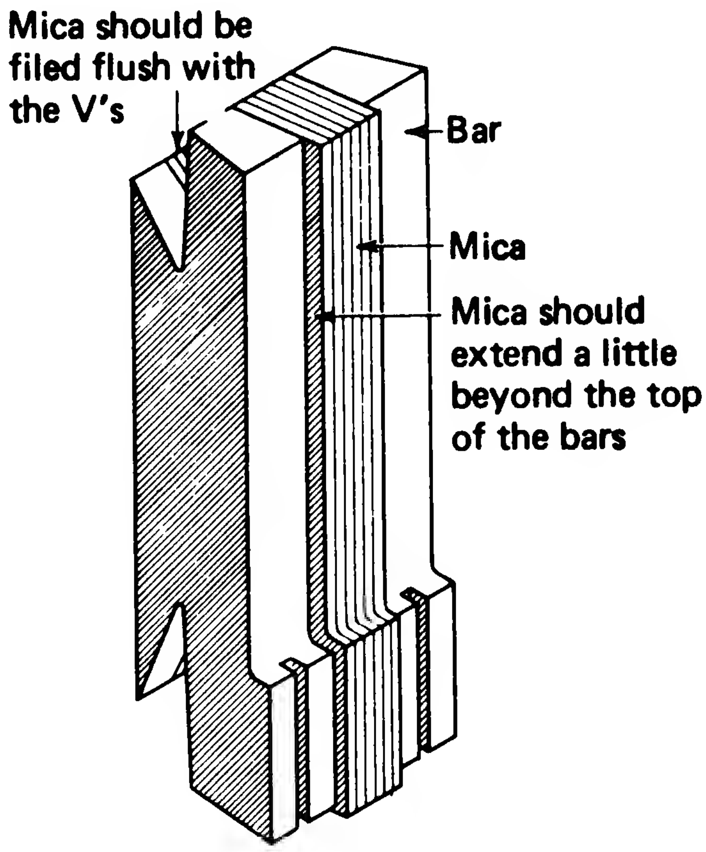


Fig. 5-101. The appearance of mica segments after they have been cut and filed to the same shape as the commutator bars.

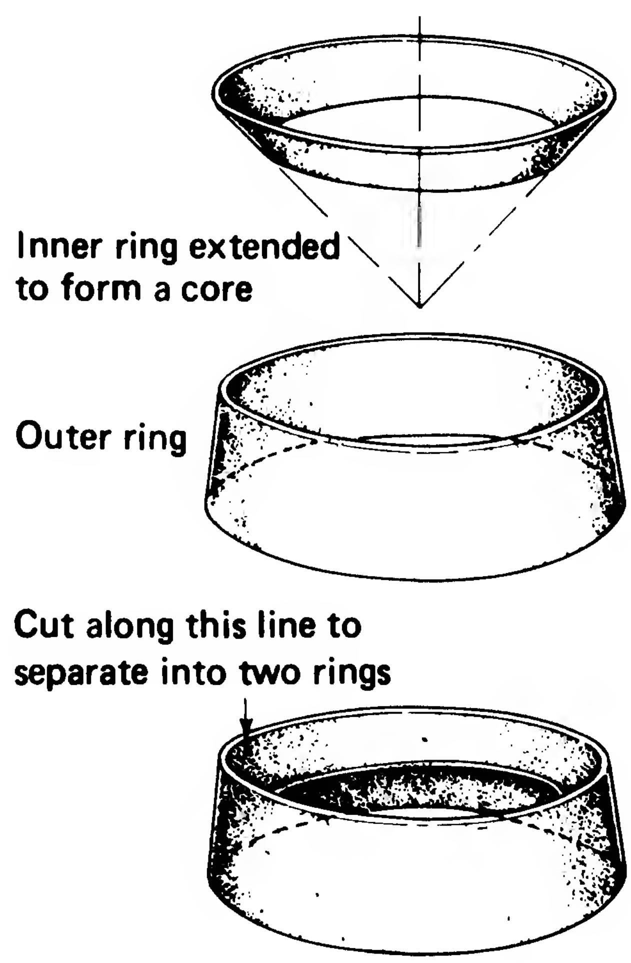


Fig. 5-102. A mica V ring consists of an inner and outer ring.

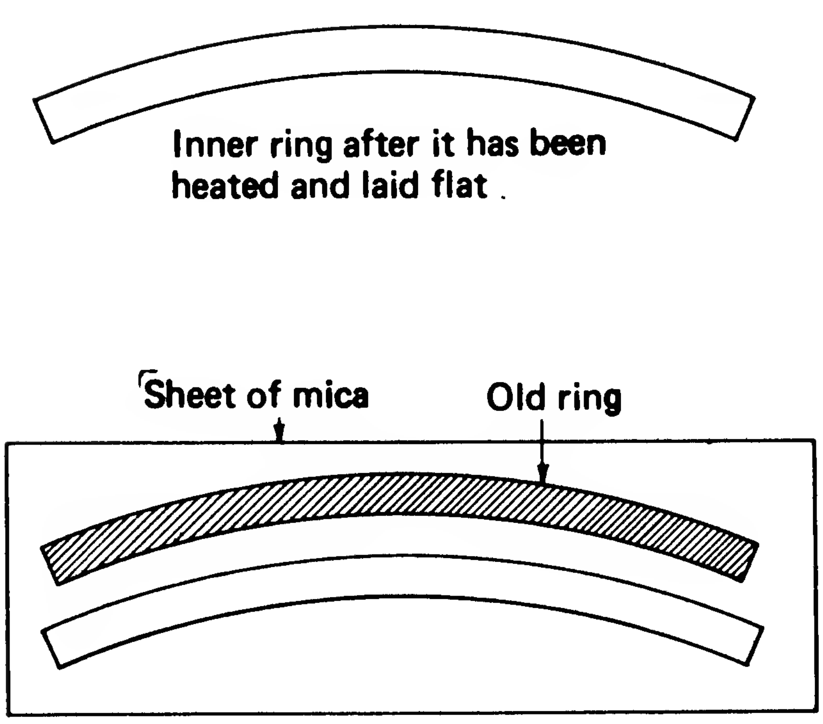


Fig. 5-103. Using the old V ring as a template to mark off the outline of the new ring.

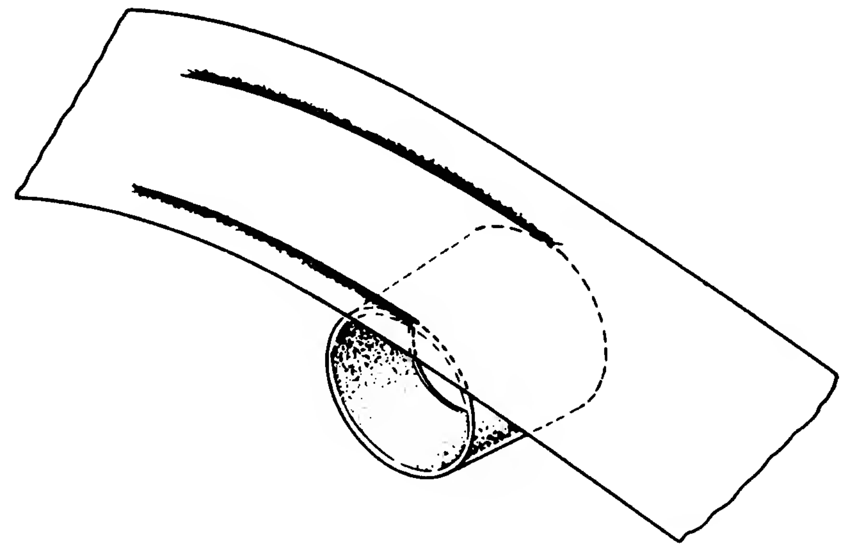


Fig. 5-104. A method of making a template by placing a piece of paper over the mica ring and pressing at the edges so that it will leave a mark on the paper.

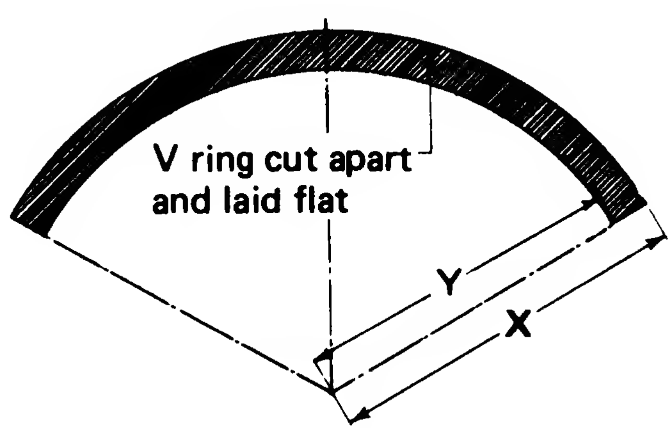


Fig. 5-105. The appearance of a section of a cone cut through and laid flat.

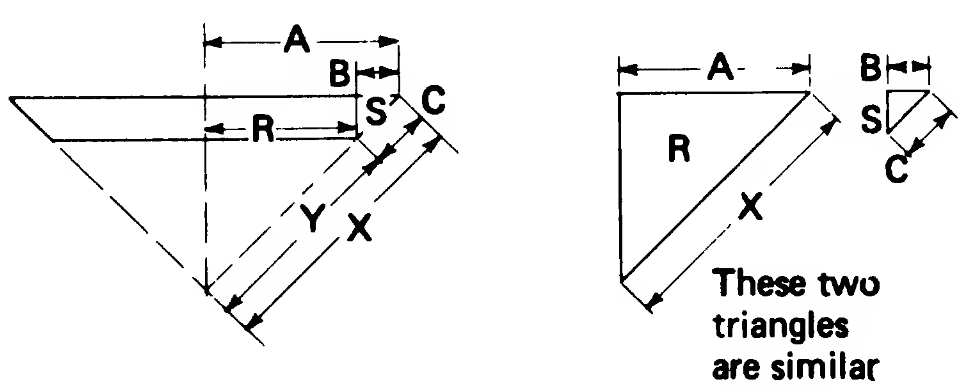


Fig. 5-106. Distances *A, B,* and *C* obtained from actual measurement on the iron V ring. These are necessary in order to get the radius *x*.

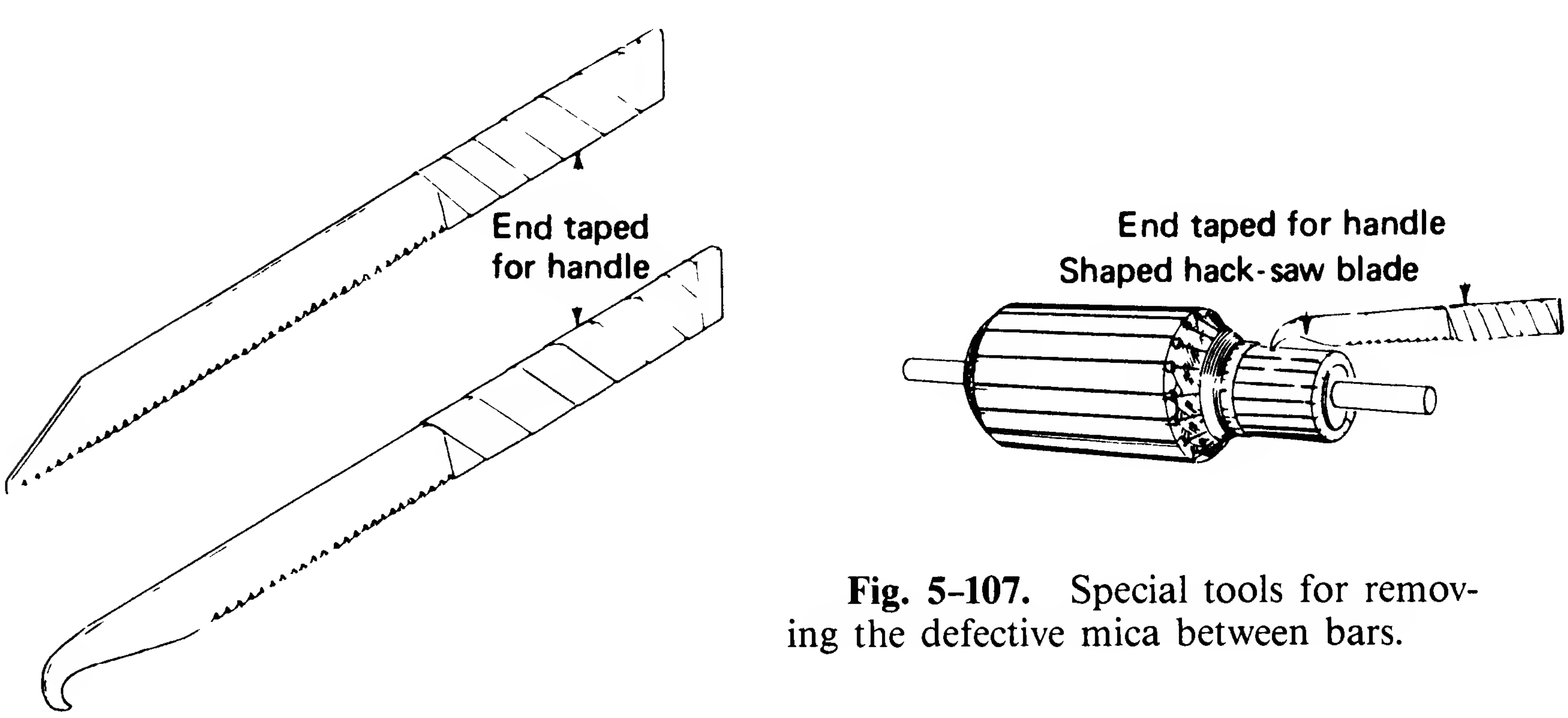


Fig. 5-107. Special tools for removing the defective mica between bars.

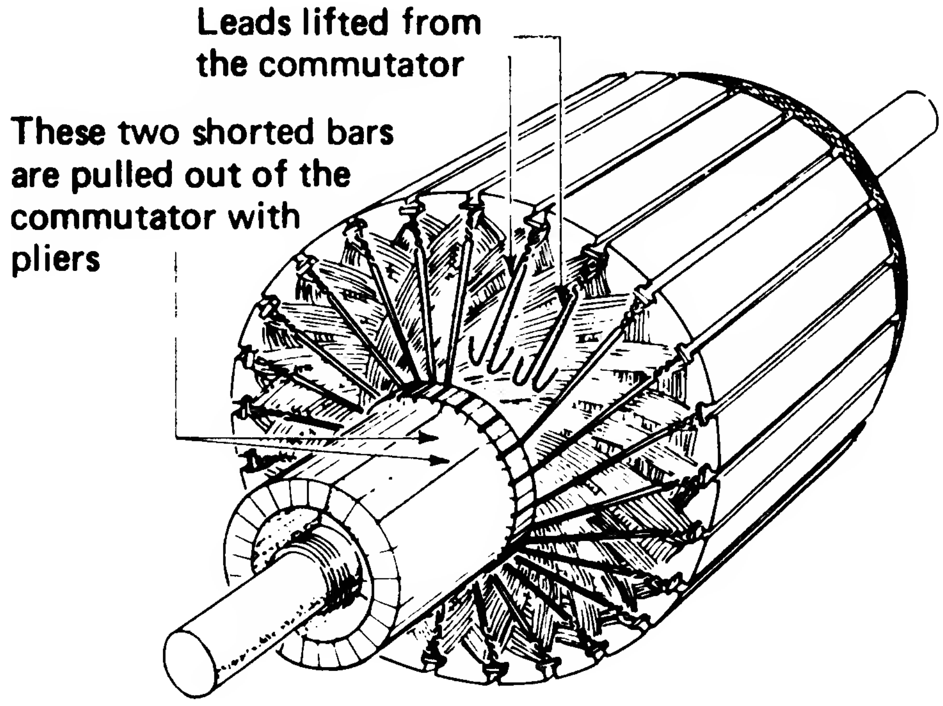


Fig. 5-108. A step in removing shorted bars.

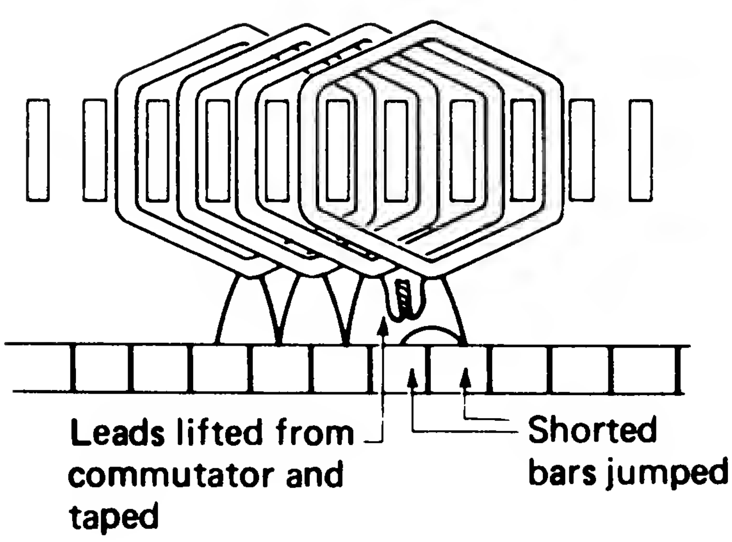
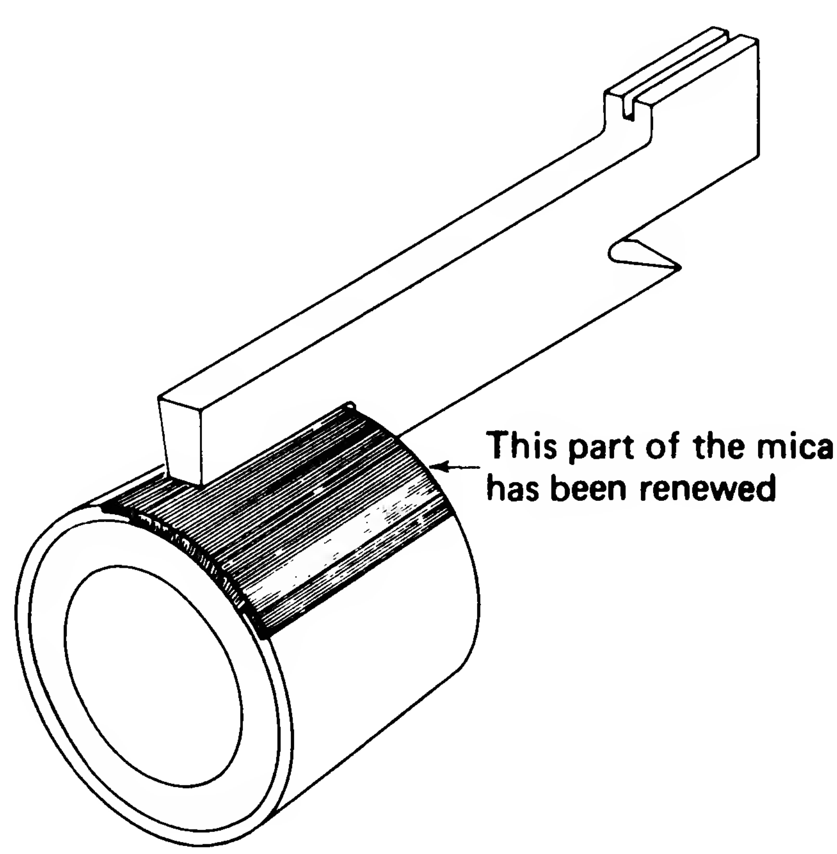


Fig. 5-109. A quick repair that can be made if two bars are shorted.

Fig. 5-110. A patch placed on the outer V ring.



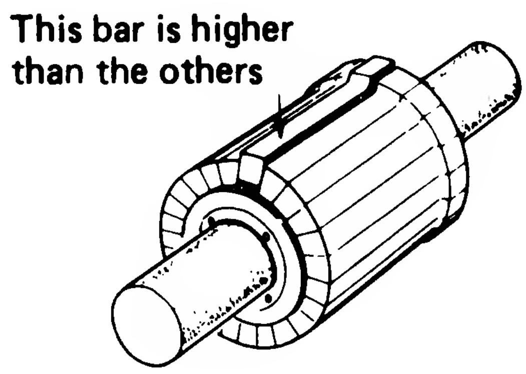


Fig. 5-111. A high bar in a commutator.

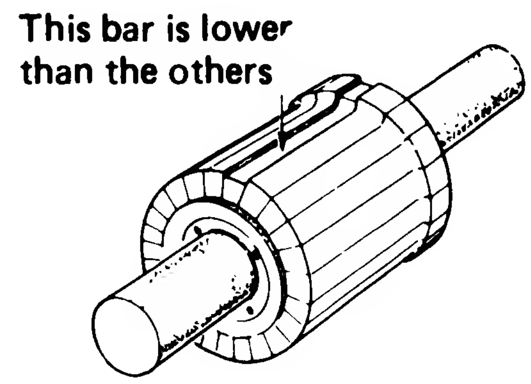


Fig. 5-112. A low bar in a commutator.

Fig. 5-113. (*Left*) a commutator correctly undercut. (*Right*) An improperly undercut commutator.

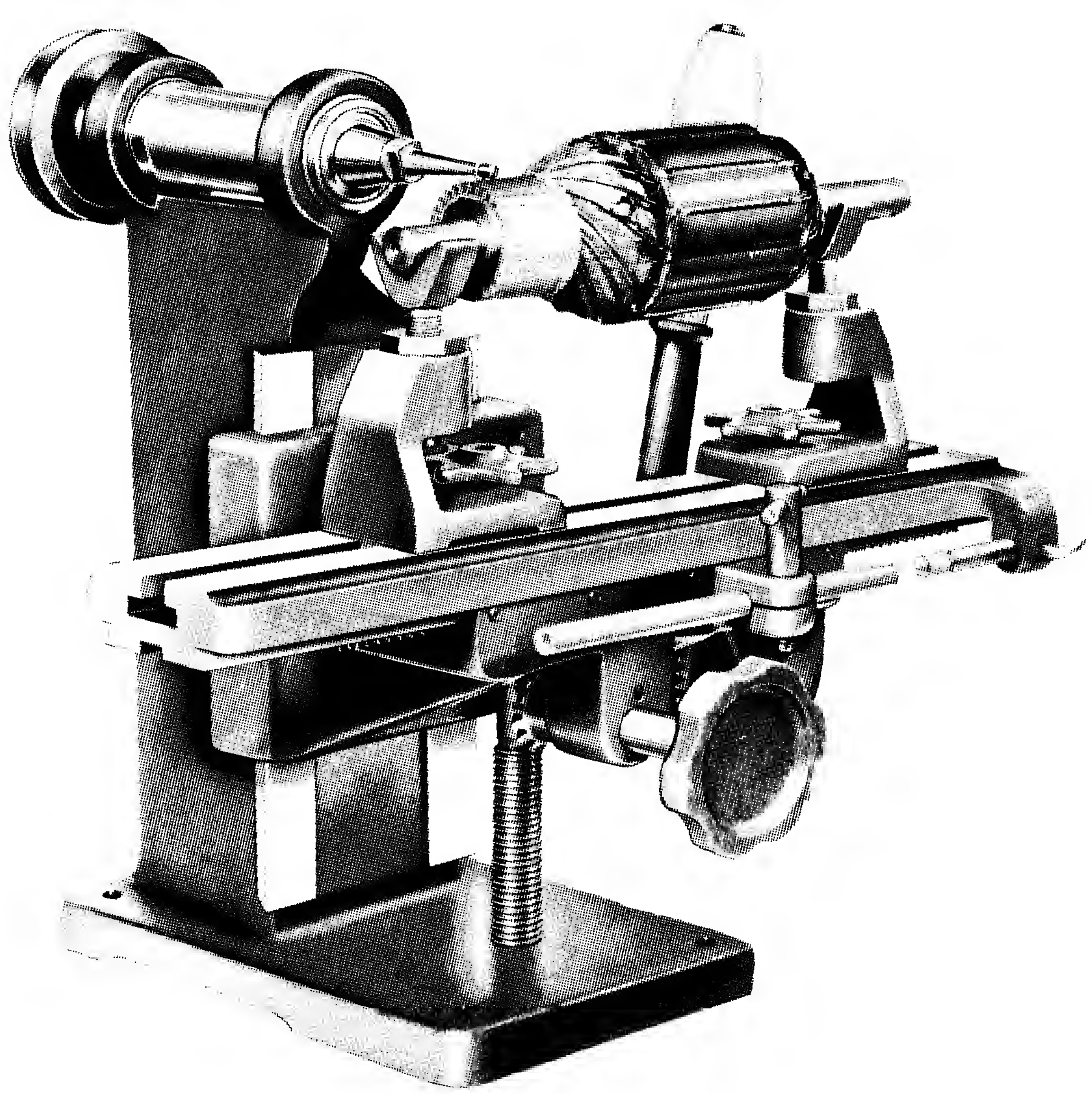


Fig. 5-114. Peerless Mica undercutter. (*Peerless Tool Division Cam Industries Inc.*)

CHAPTER 6
Direct-current Motors

Fig. 6-1. A dc motor. (*Baldor Electric Co.*)

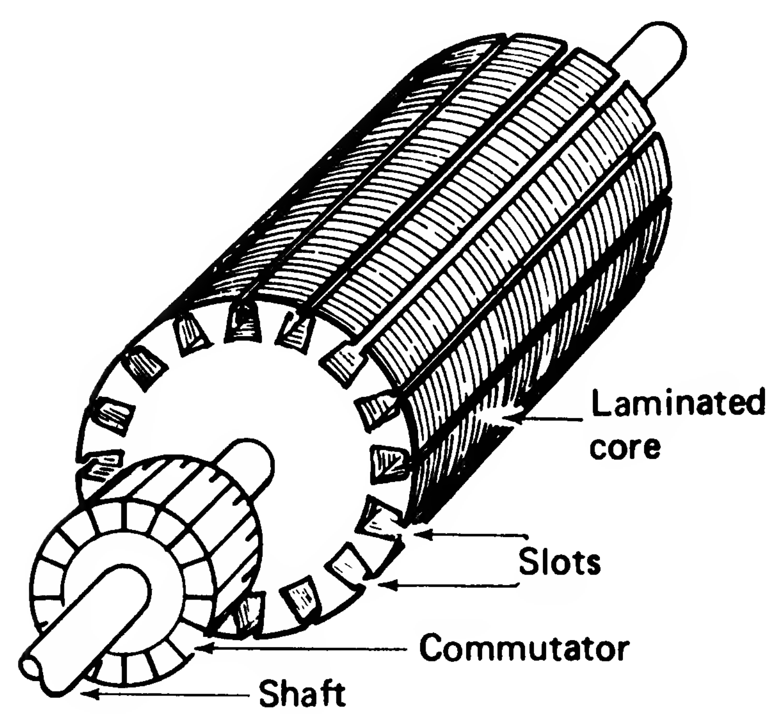


Fig. 6-2. The armature of a dc motor before windings are inserted in slots.

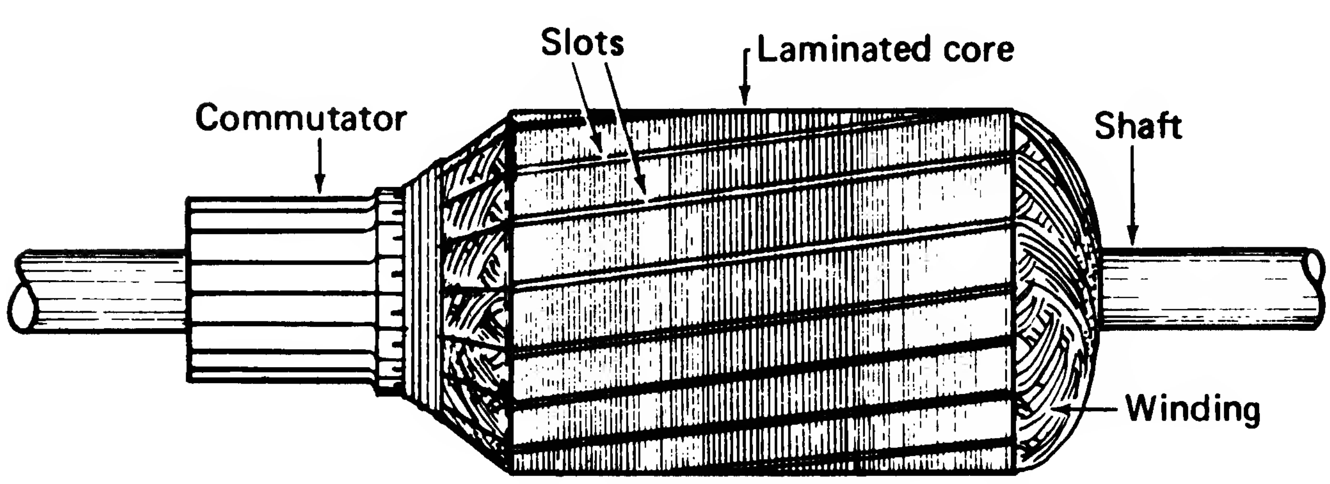


Fig. 6-3. The armature with skewed slots and windings in place.

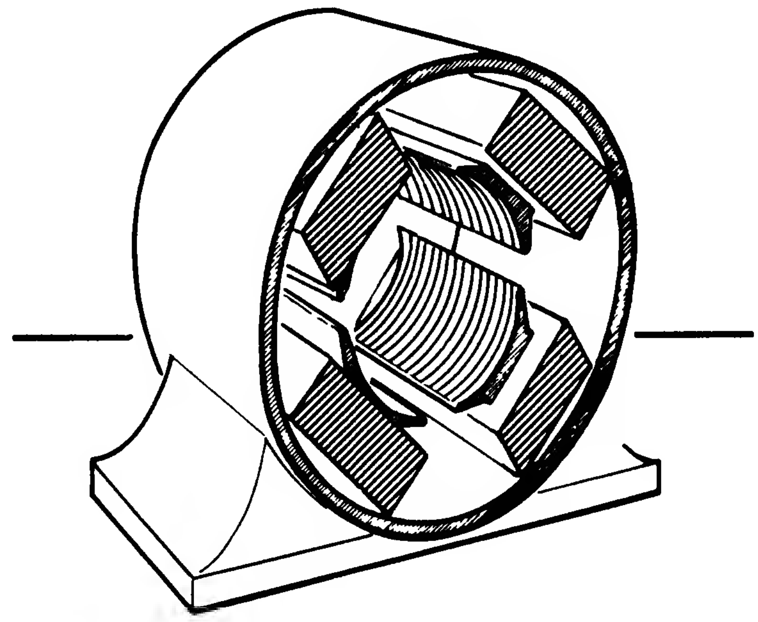


Fig. 6-4. A complete field assembly and frame of a dc motor.

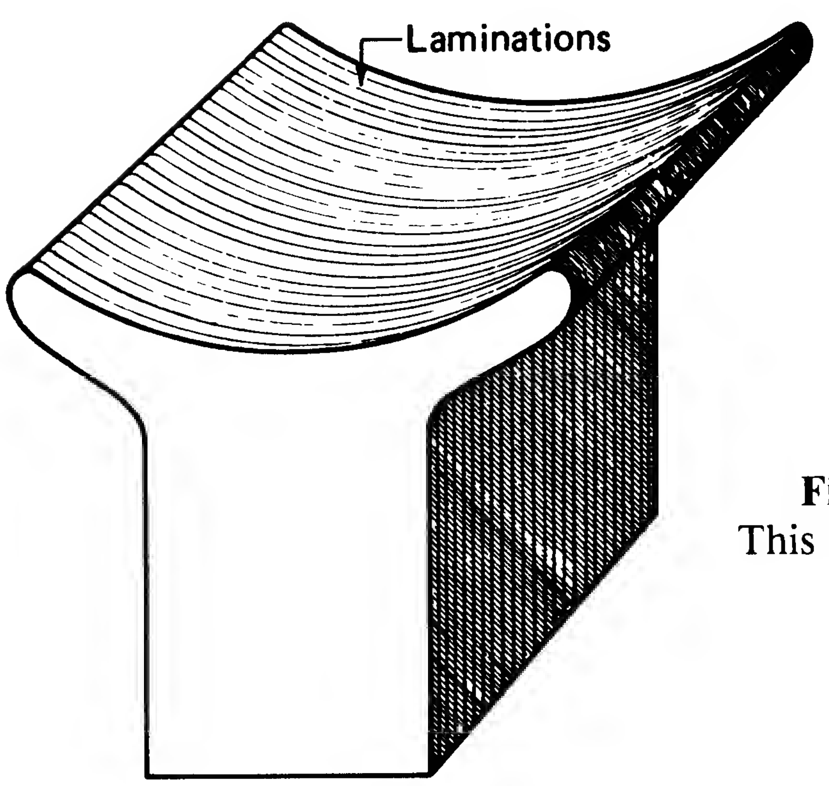


Fig. 6-5. A laminated field core. This may be bolted to the frame.

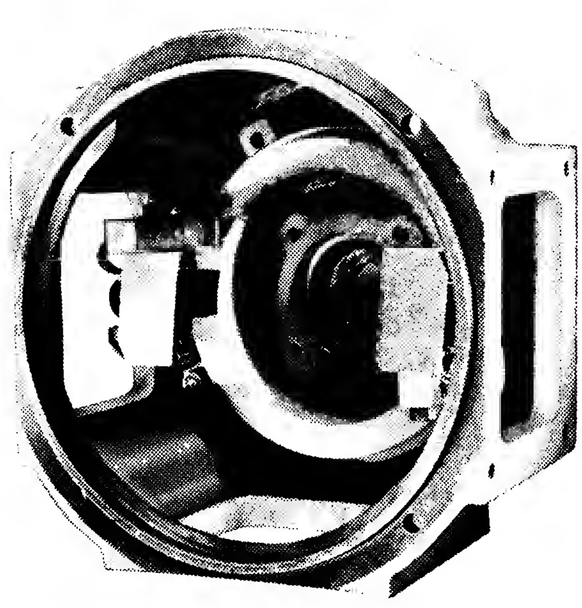


Fig. 6-6. An end plate of a dc motor showing brush rigging. (*General Electric Co.*)

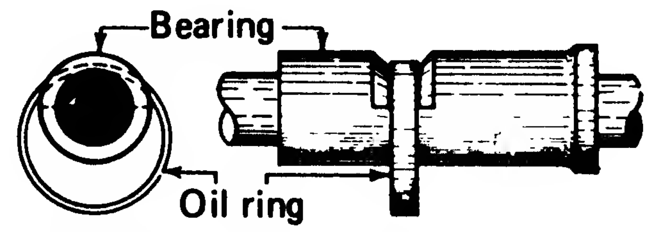


Fig. 6-7. Construction of sleeve bearing and oil ring.

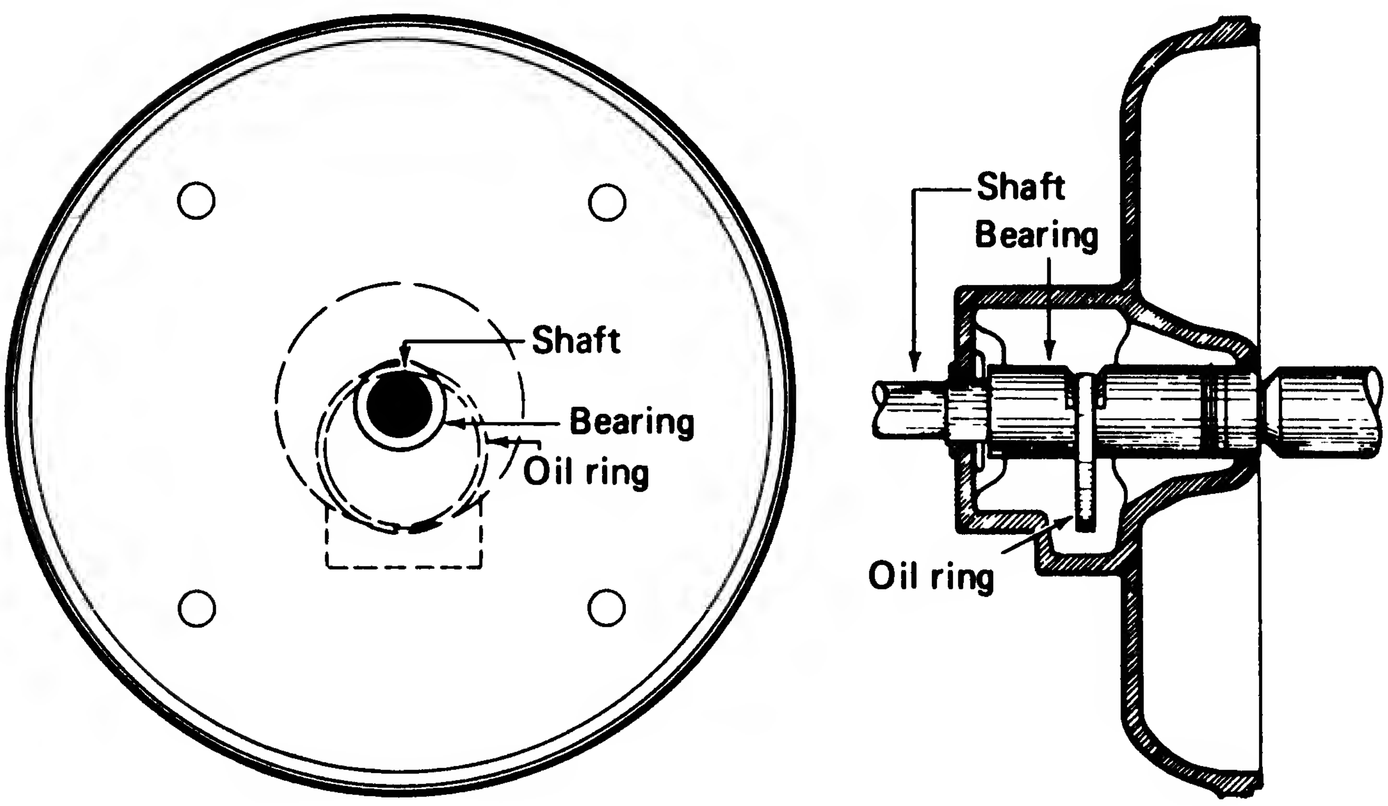


Fig. 6-8. A sleeve bearing assembled on an end plate.

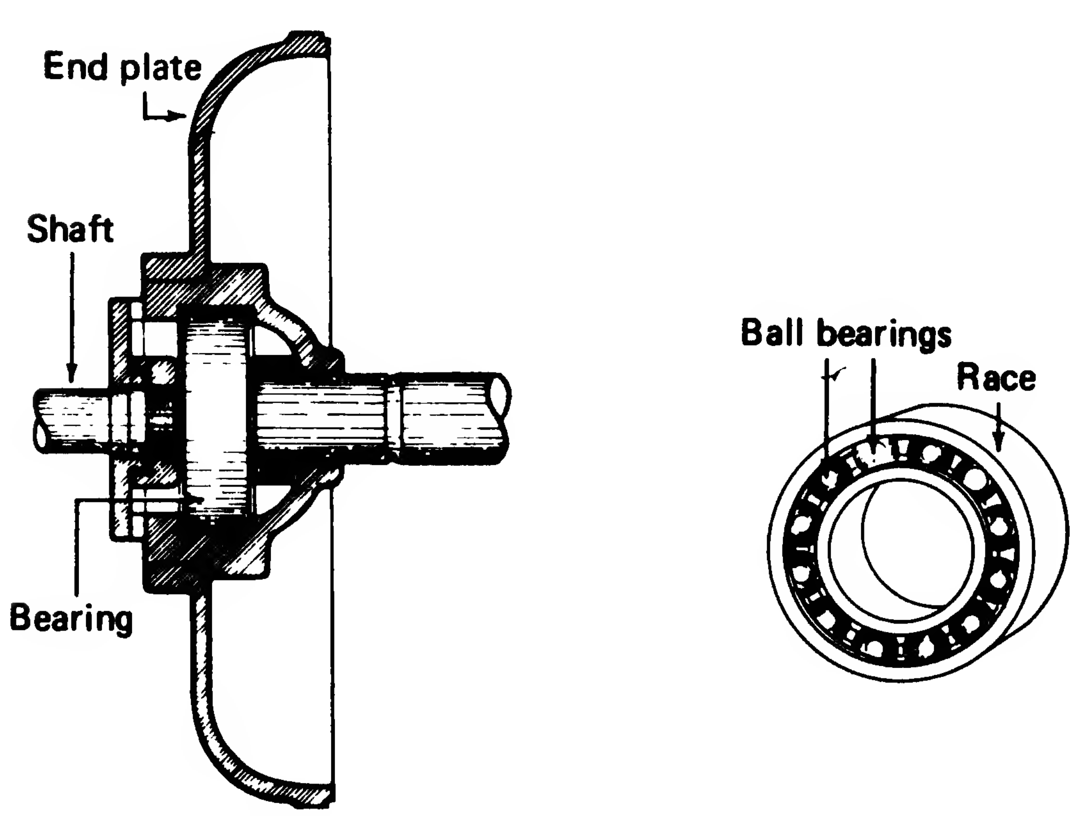


Fig. 6-9. The ball bearing at right mounted in the end plates as shown.

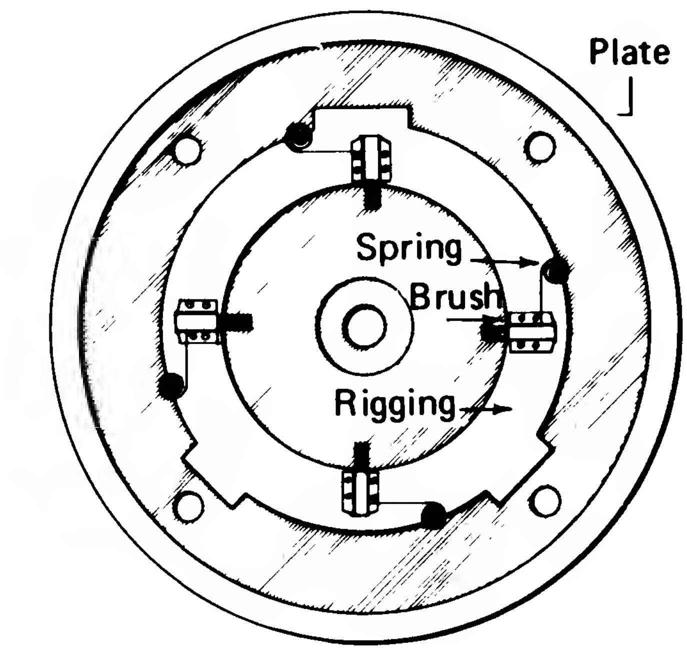


Fig. 6–10. The brush rigging attached to the end plate.

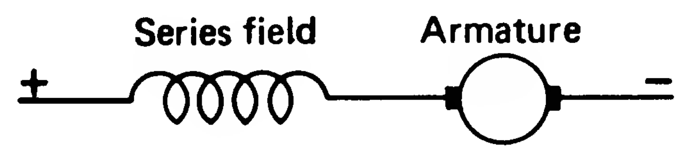


Fig. 6–11. The field and armature connection of a series motor.

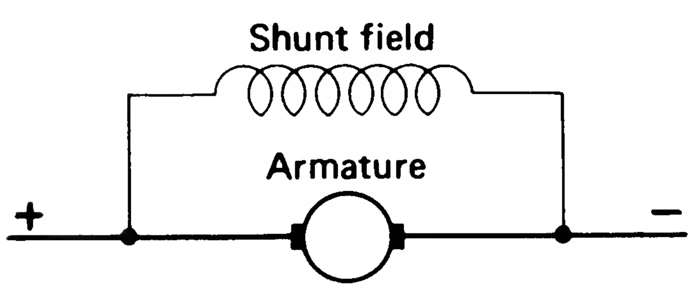


Fig. 6–12. The field and armature connection of a shunt motor.

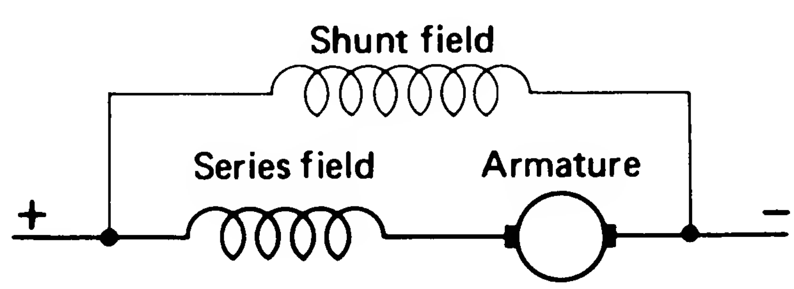


Fig. 6–13a. The field and armature connection of a compound motor.

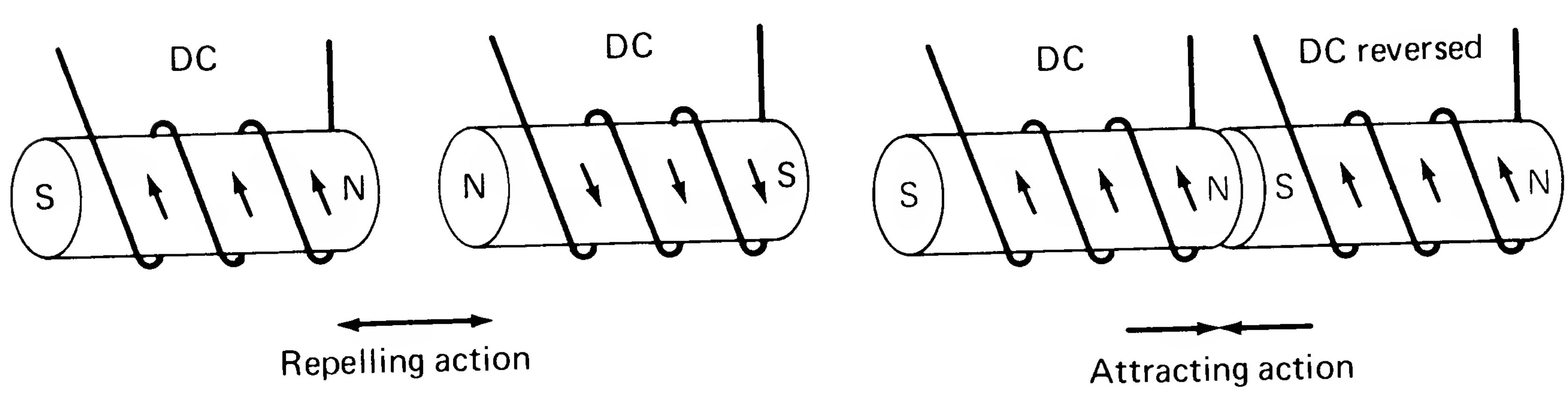


Fig. 6–13b. Repelling and attracting action of two electromagnets.

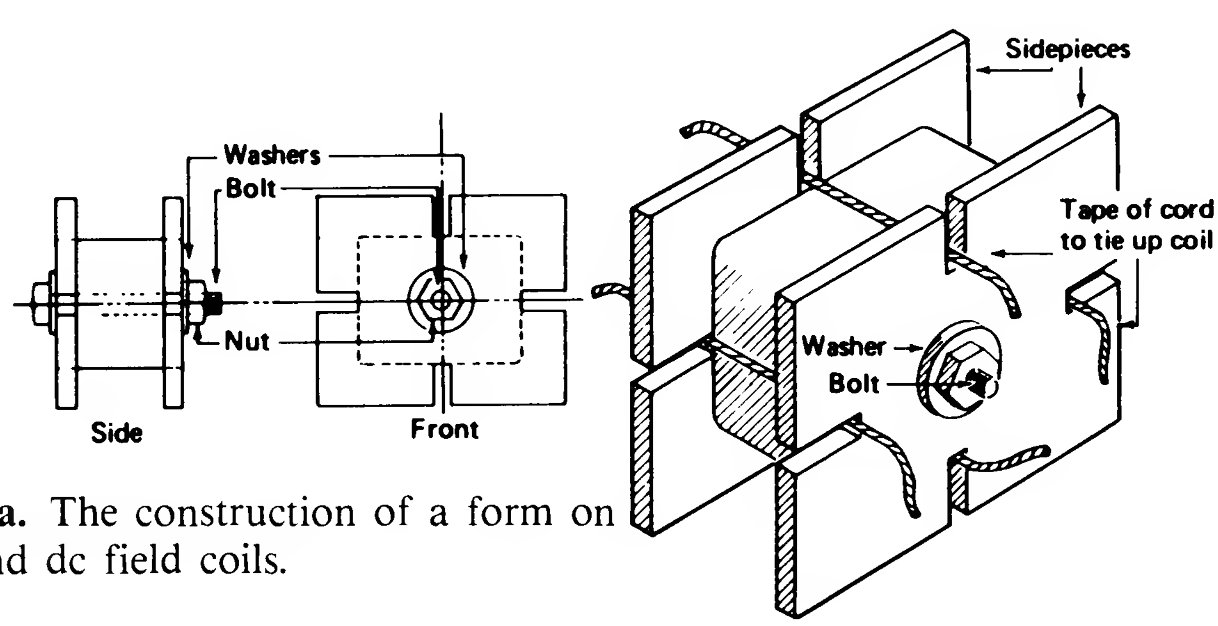


Fig. 6–14a. The construction of a form on which to wind dc field coils.

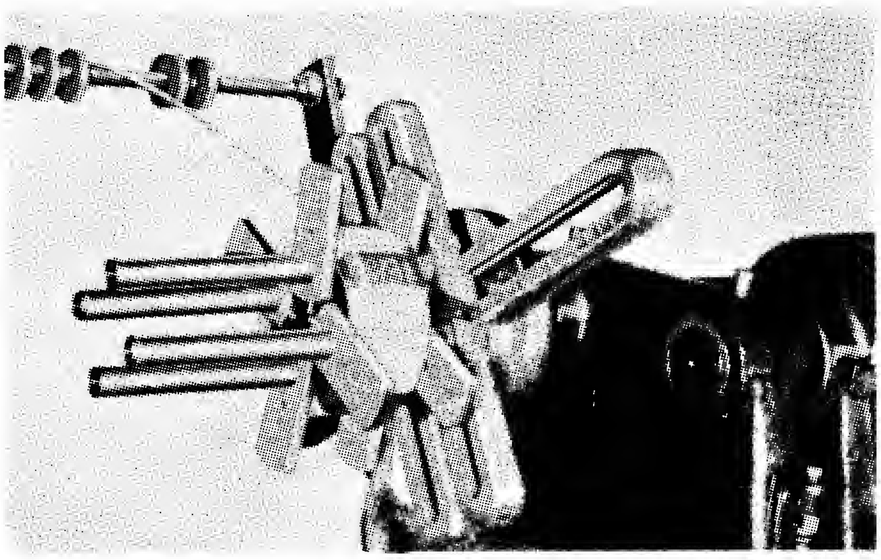


Fig. 6-14b. Coil winder head. *(Crown Industrial Products)*

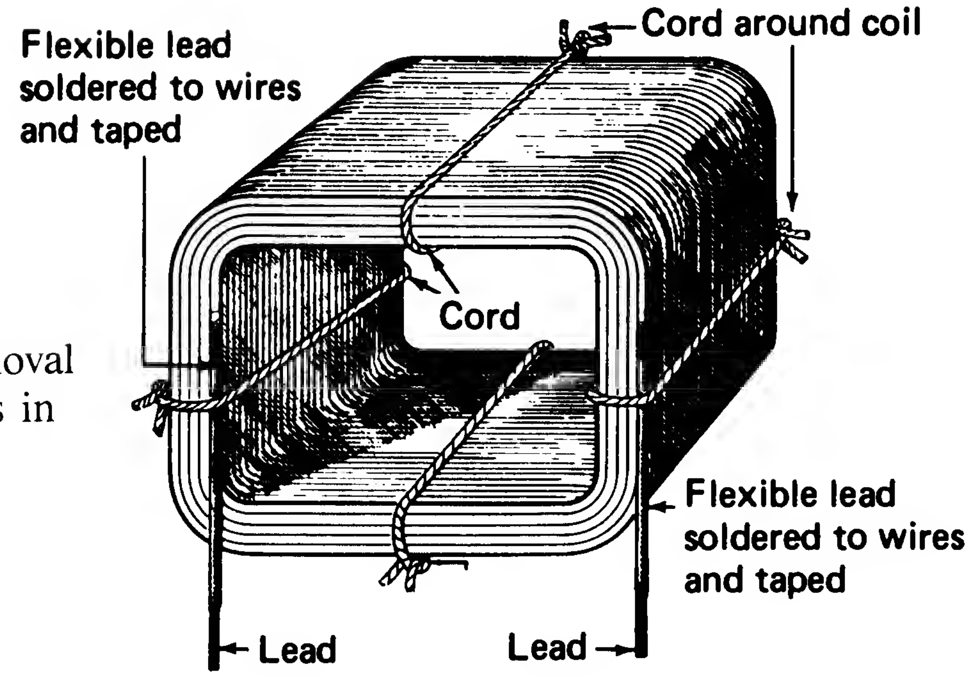


Fig. 6-15. A field coil after removal from form. The cord holds the turns in place.

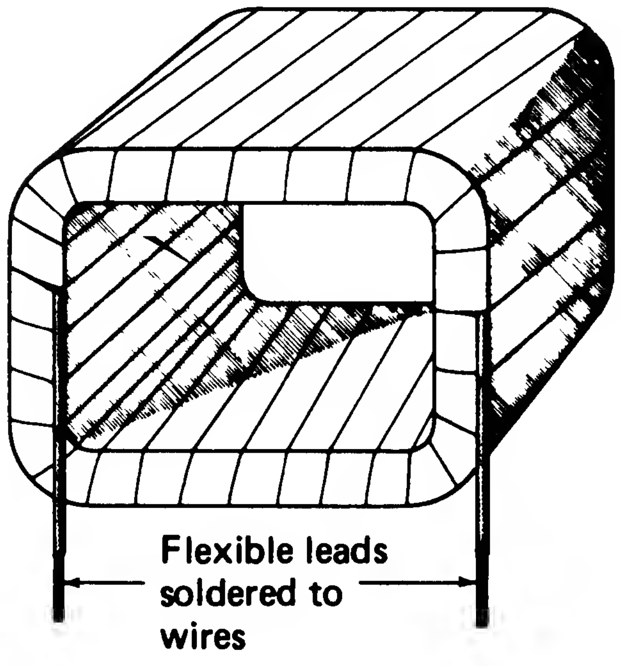


Fig. 6-16. A series-field coil is taped after flexible leads are soldered to the beginning and end of the coil. The coil is usually taped with a layer of cellulose acetate film tape.

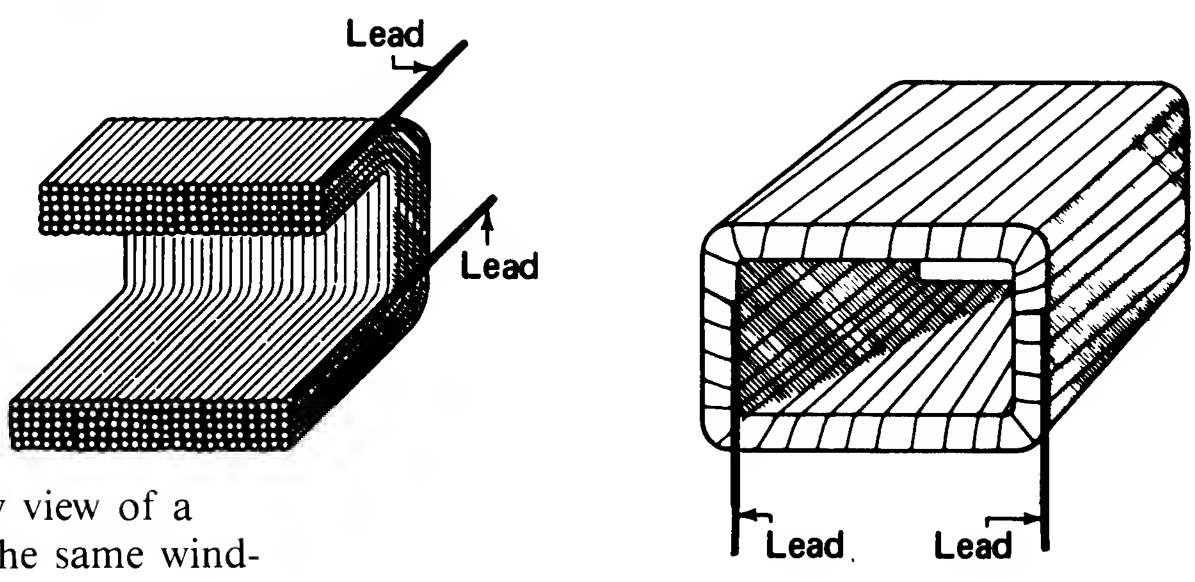


Fig. 6-17. A cutaway view of a shunt-field winding and the same winding after taping.

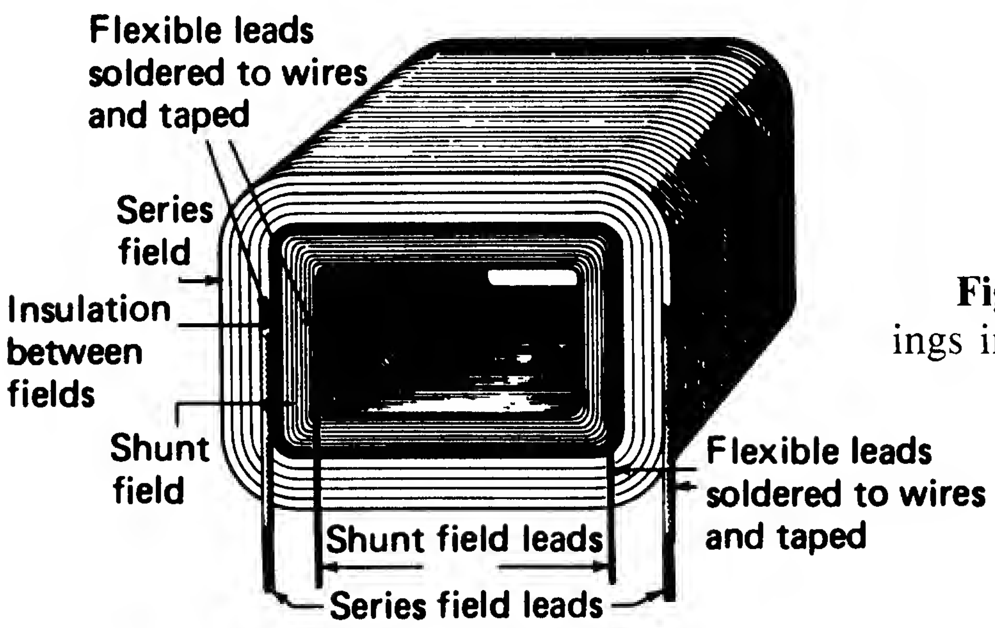


Fig. 6-18. The arrangement of windings in a compound field coil.

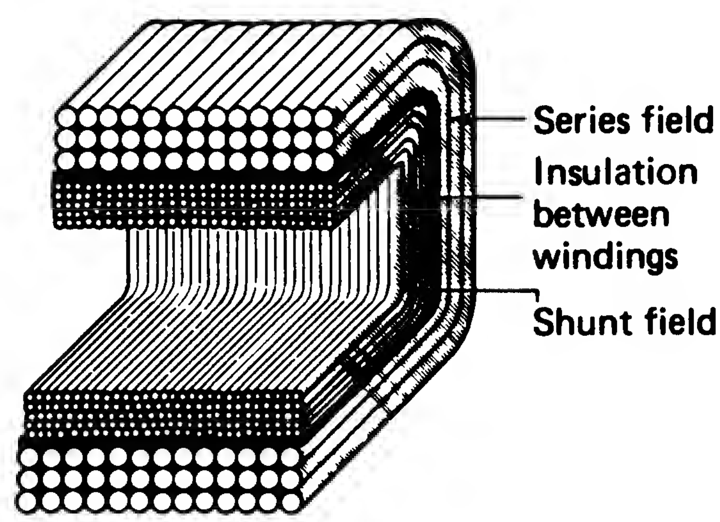


Fig. 6-19. A cutaway view of a compound-field coil.

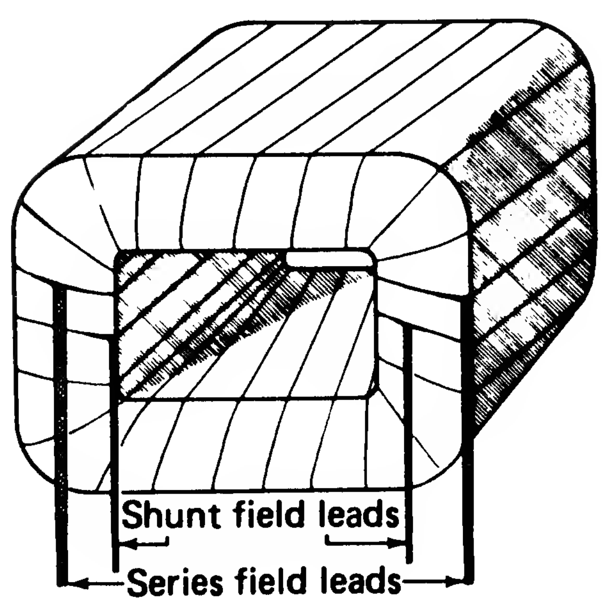


Fig. 6-20. A compound-field coil and its leads after taping.

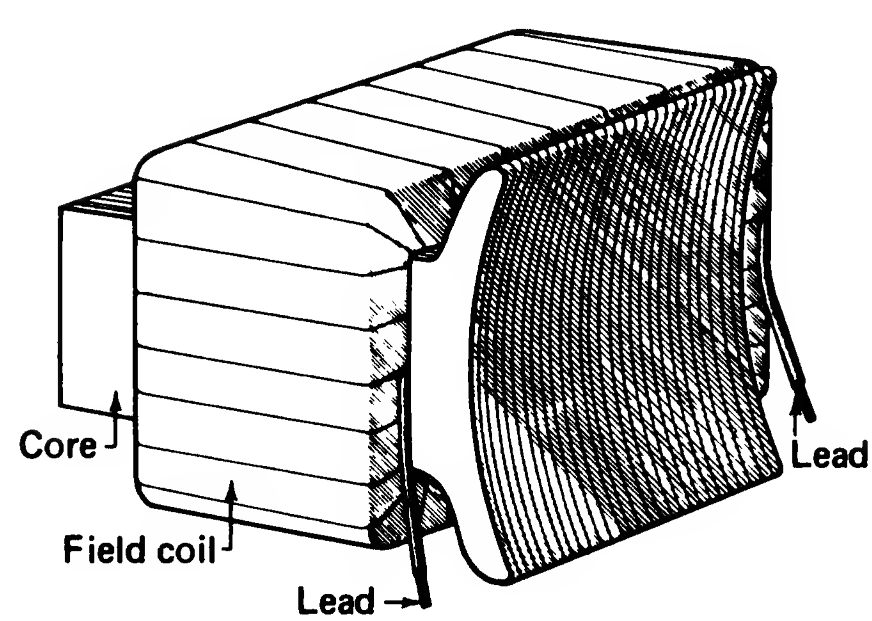


Fig. 6-21. A field coil assembled on its core.

Figures **6**–18; **6**–19; **6**–20; **6**–21

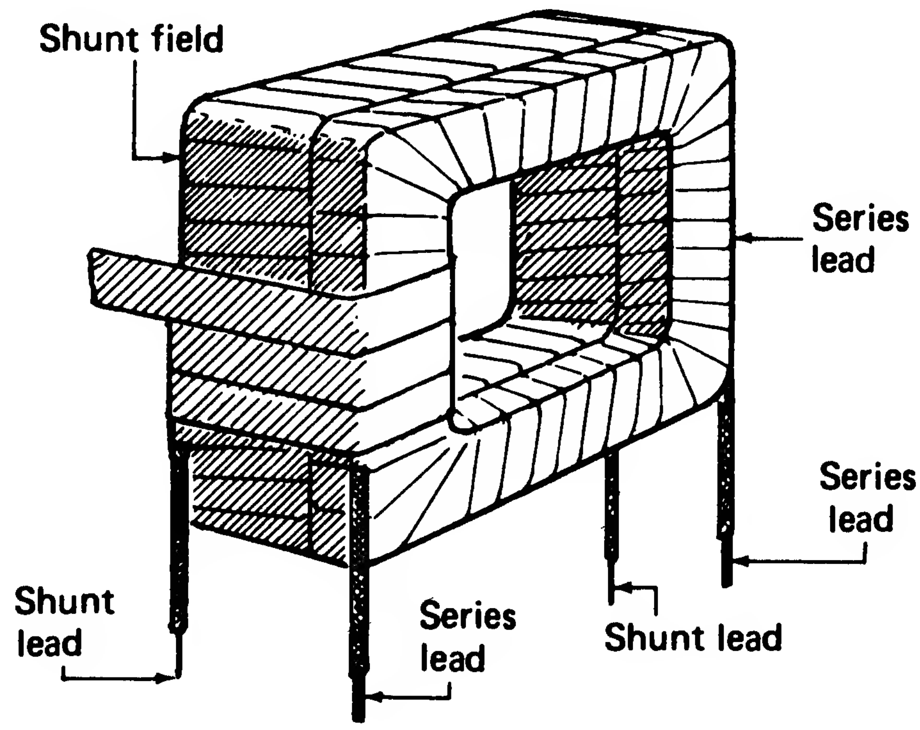
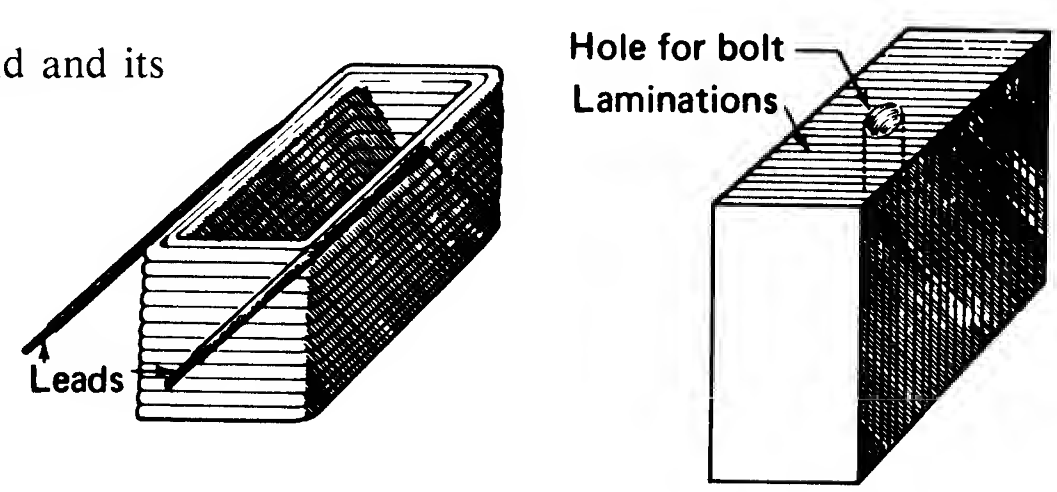


Fig. 6–22. A compound field for a large motor. The shunt and series fields are wound and taped separately, then placed side by side and taped again.

Fig. 6–23. An interpole field and its core.



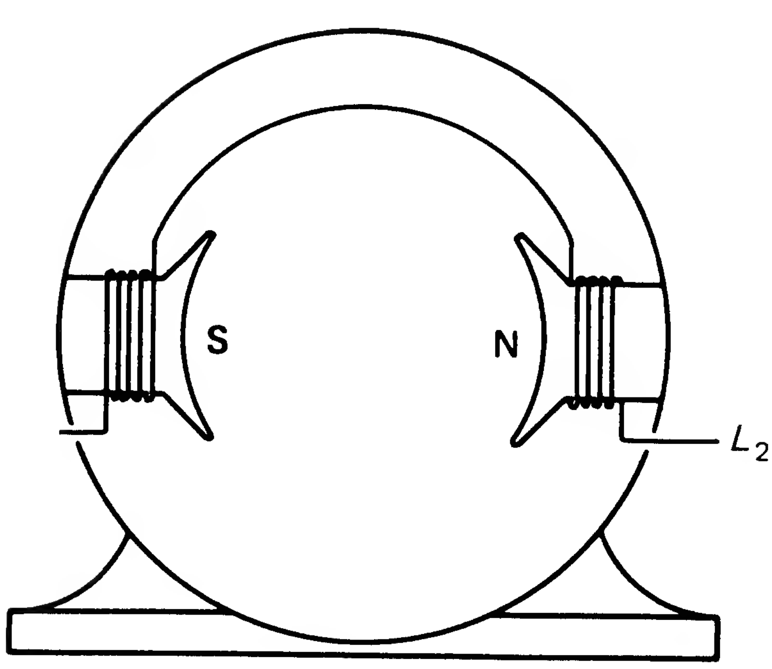


Fig. 6–24. In a two-pole motor, the fields are connected to form a north and south pole.

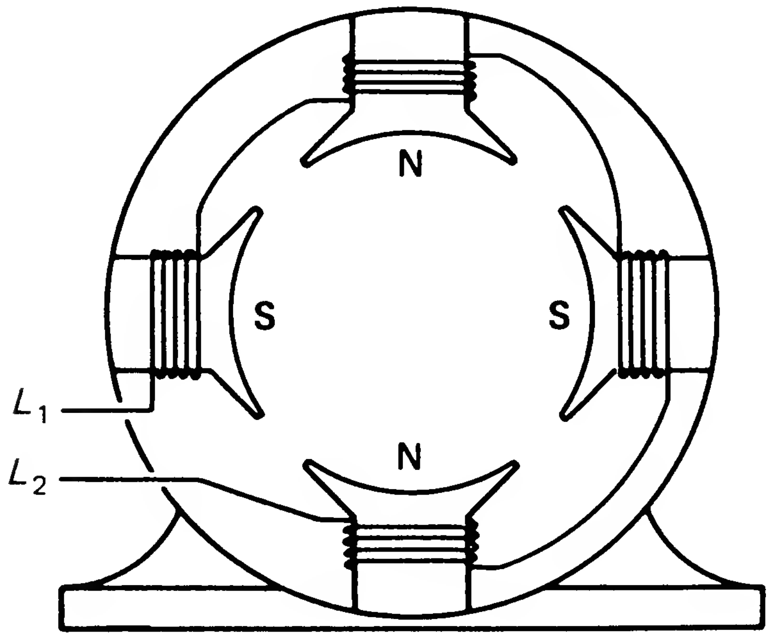


Fig. 6-25. North and south poles alternate in a four-pole motor.

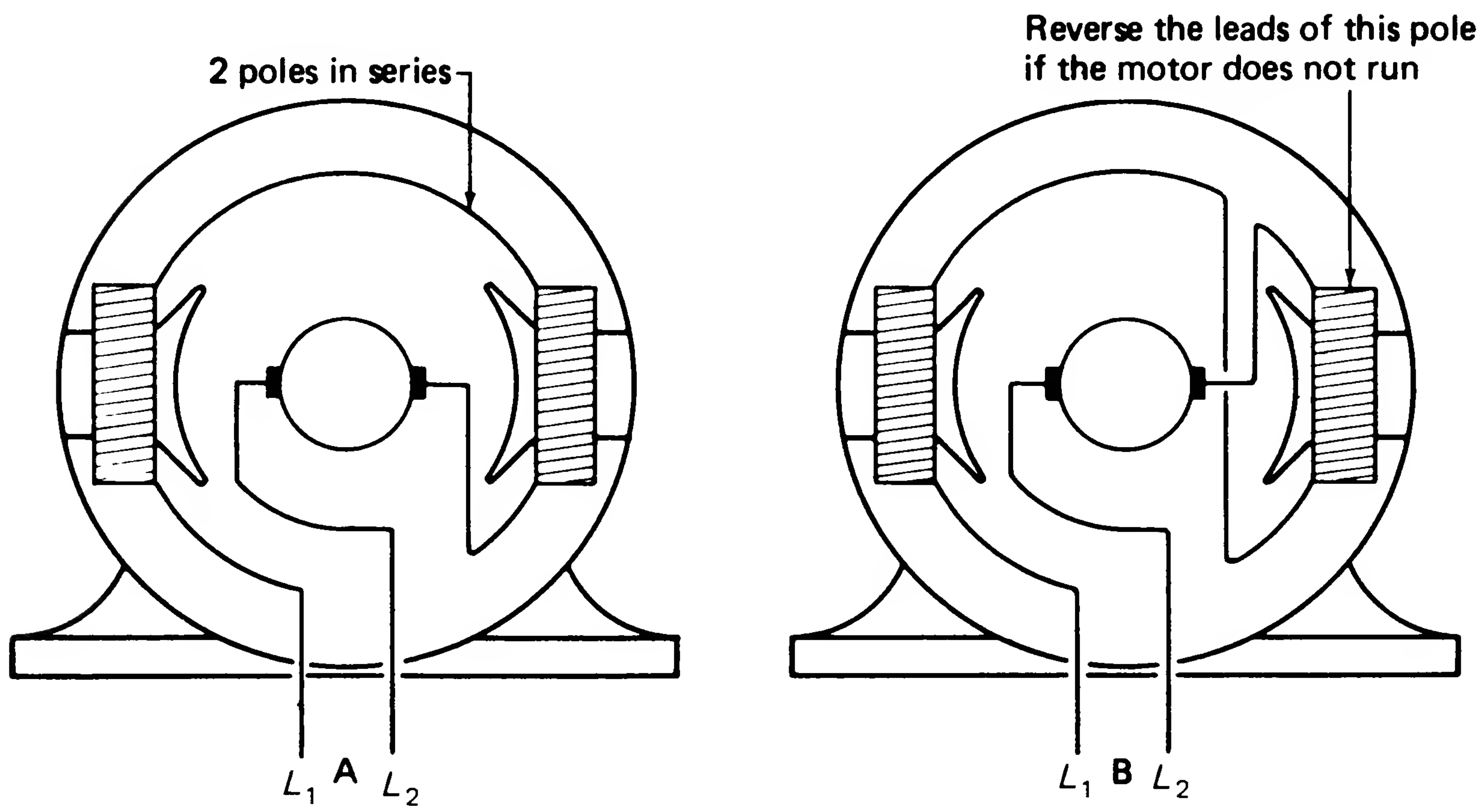


Fig. 6-26. A test for correct field polarity on a small two-pole motor.

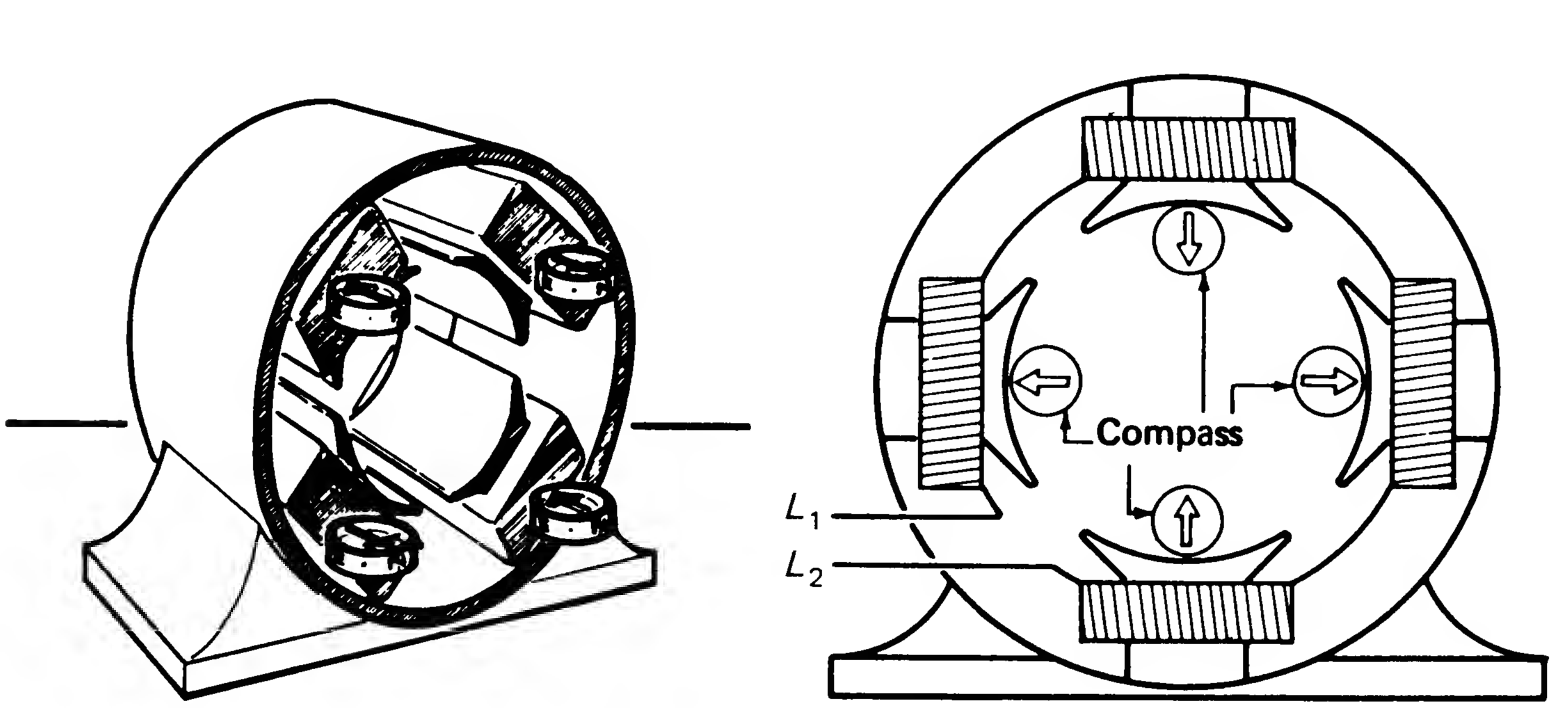


Fig. 6-27. On a four-pole motor, adjacent poles must have opposite polarity.

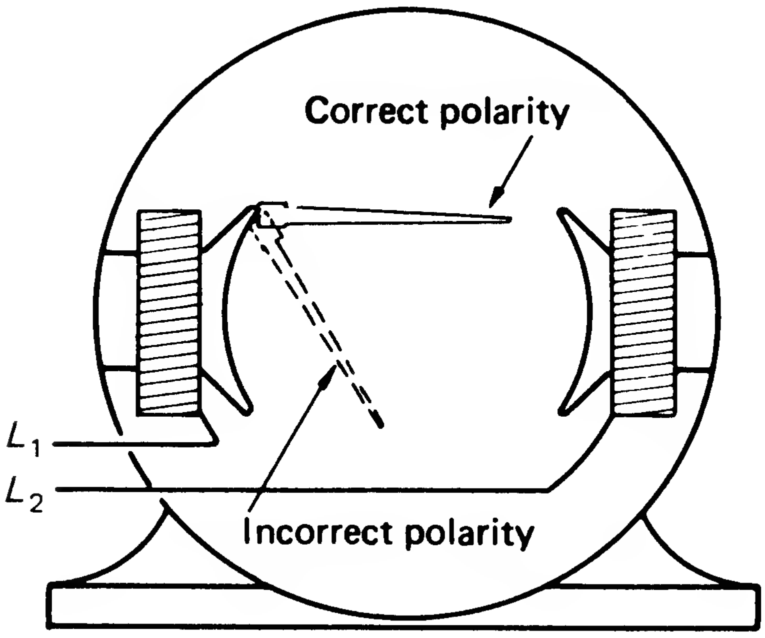


Fig. 6-28. Testing polarity of the field coils with a nail.

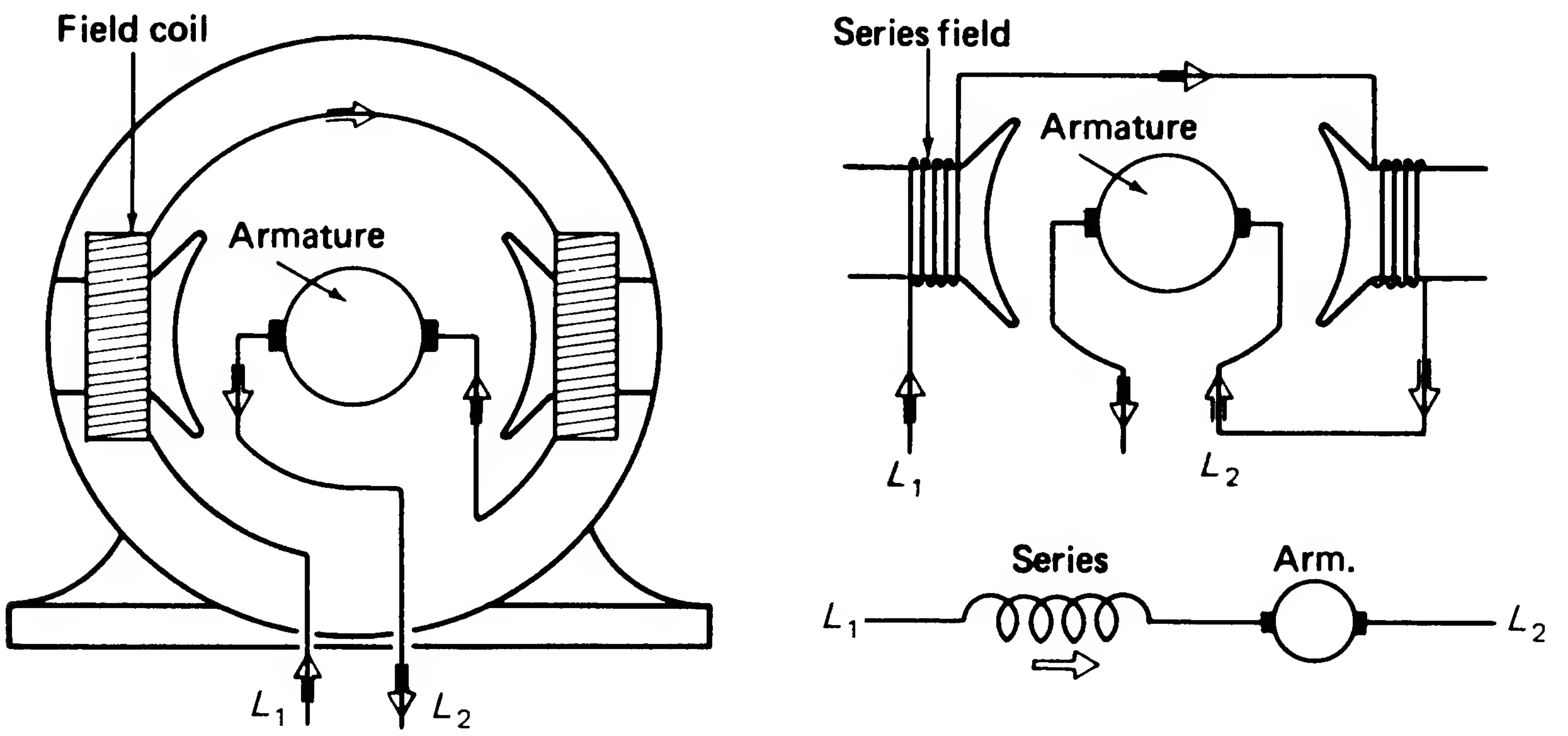


Fig. 6-29. Several methods of showing the connections of a two-pole series motor.

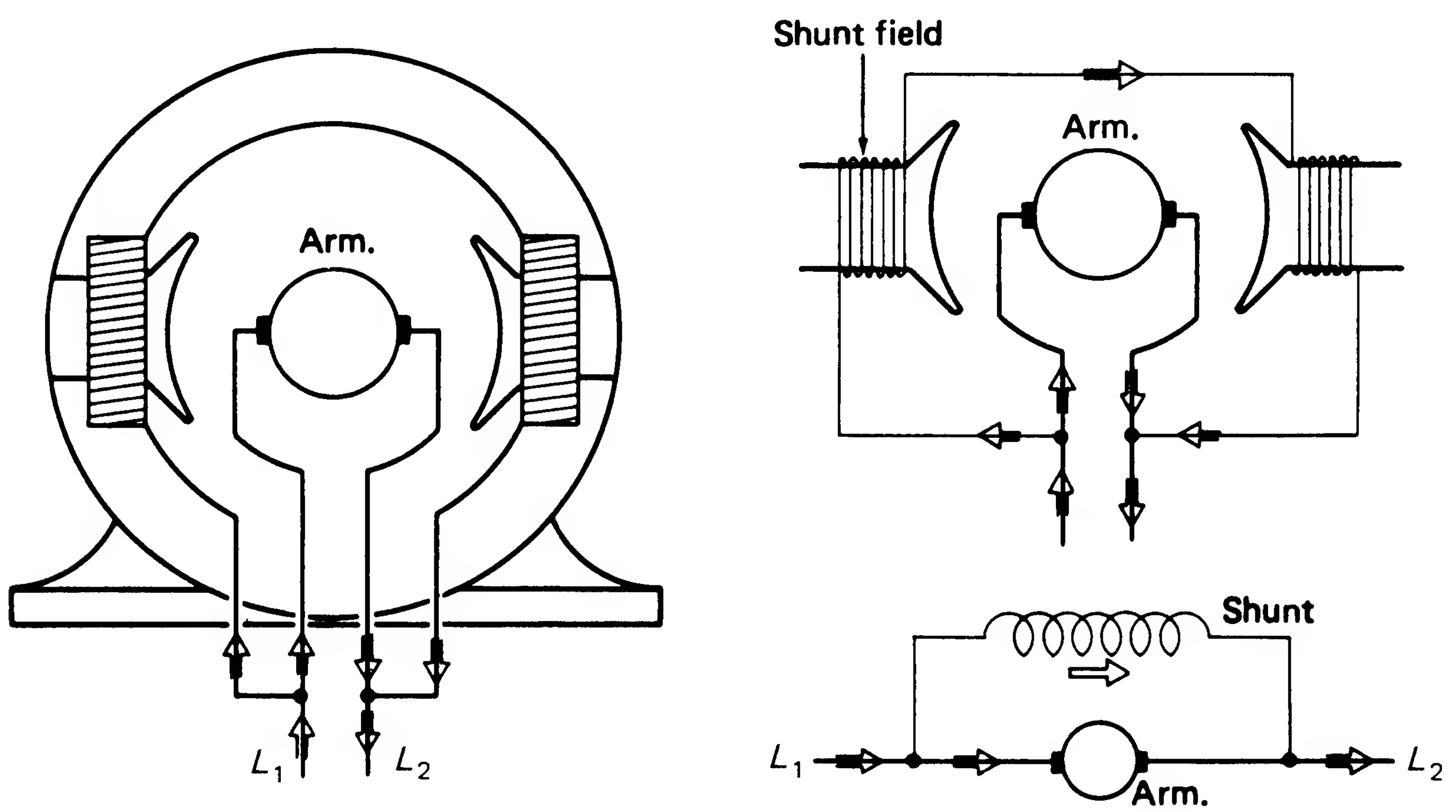


Fig. 6-30. Three methods of showing the connections of a two-pole shunt motor.

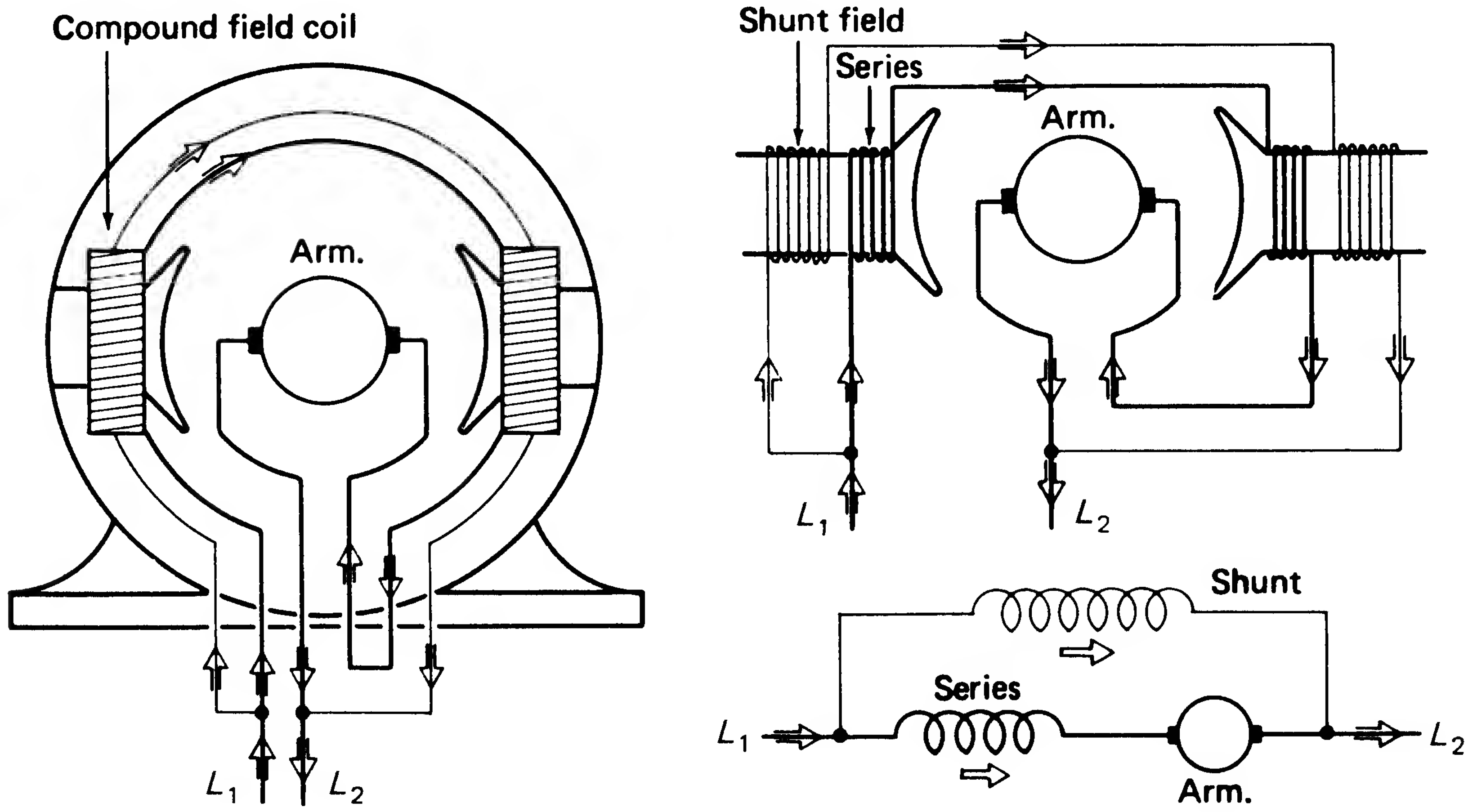


Fig. 6–31. Three methods of showing the connection of a two-pole compound motor.

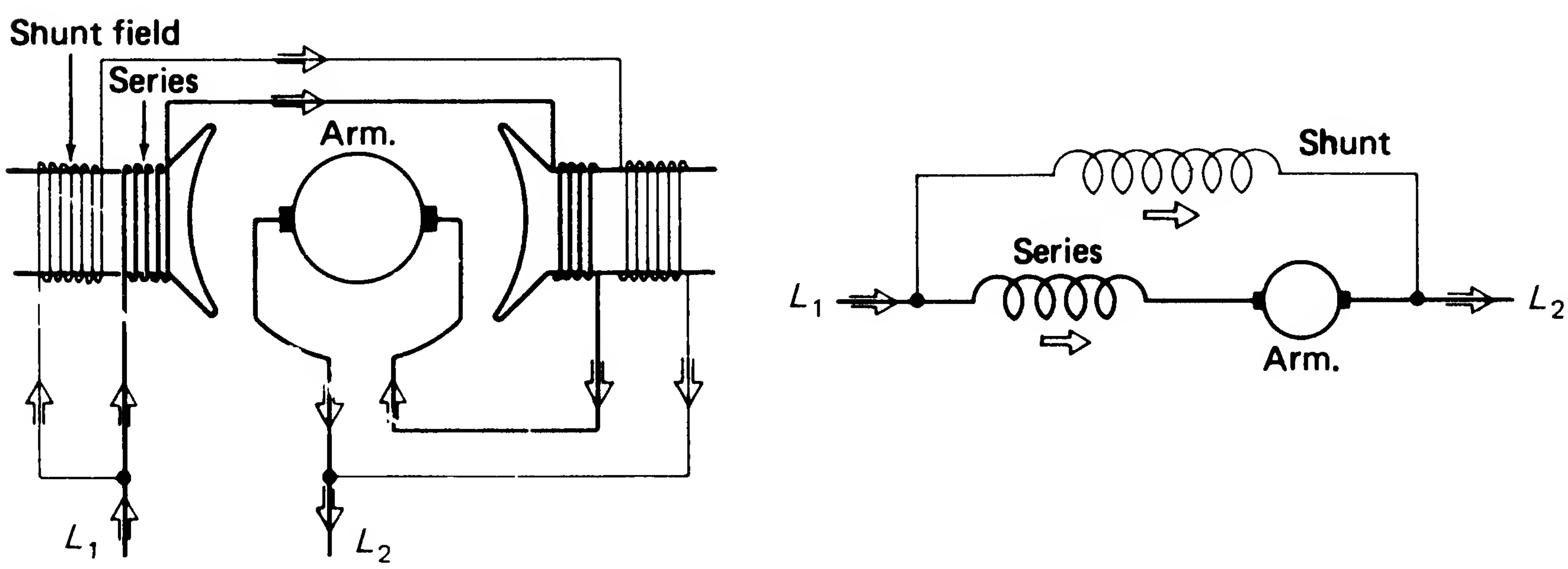


Fig. 6–32. A two-pole cumulatively compounded motor. If the current flow is in the same direction in both fields, it is called a *cumulative connection.*

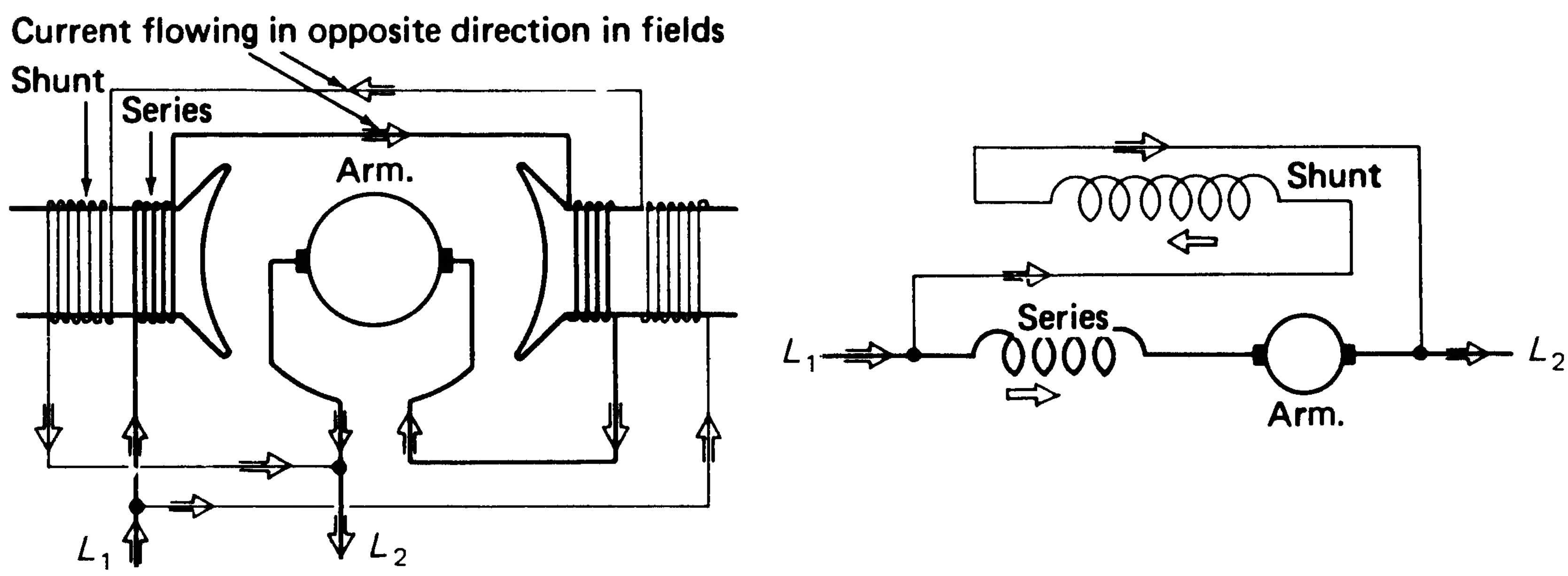


Fig. 6–33. A long-shunt, differentially connected compound motor with the current flow in opposite directions in the fields. When the shunt field is connected across the line, it is called a *long shunt.*

Figures **6**–31; **6**–32; **6**–33

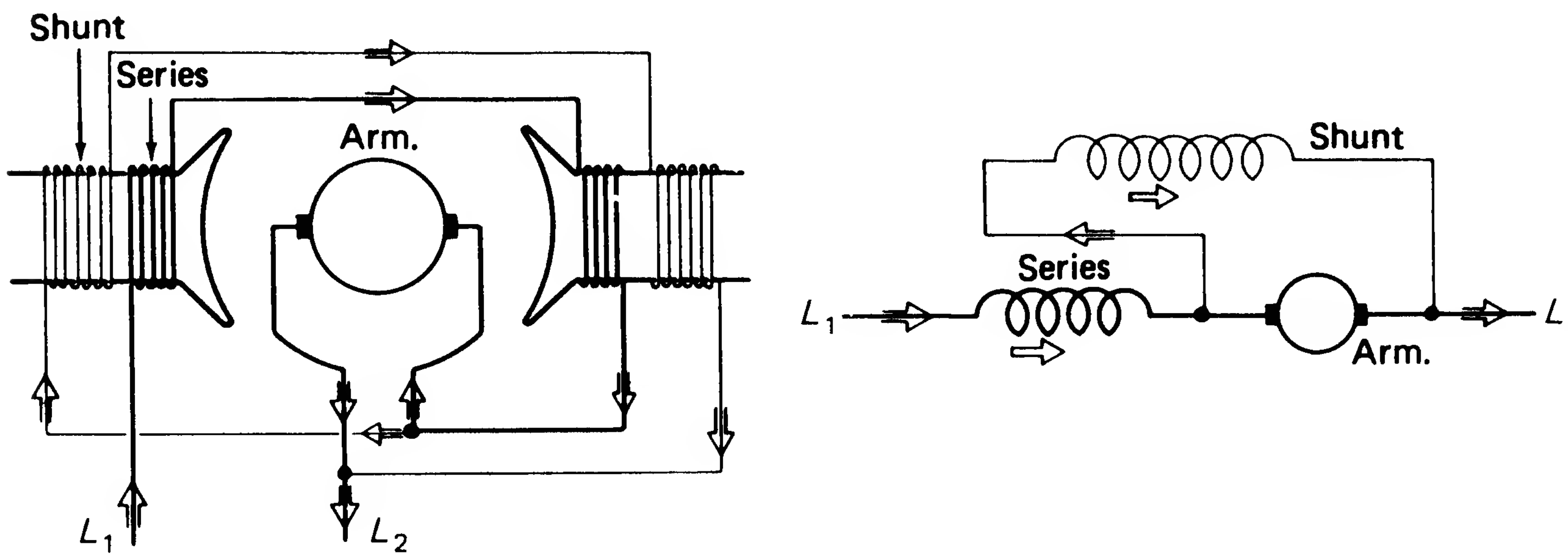


Fig. 6–34. A short-shunt cumulatively compound motor. The current in both the series and shunt fields flows in the same direction.

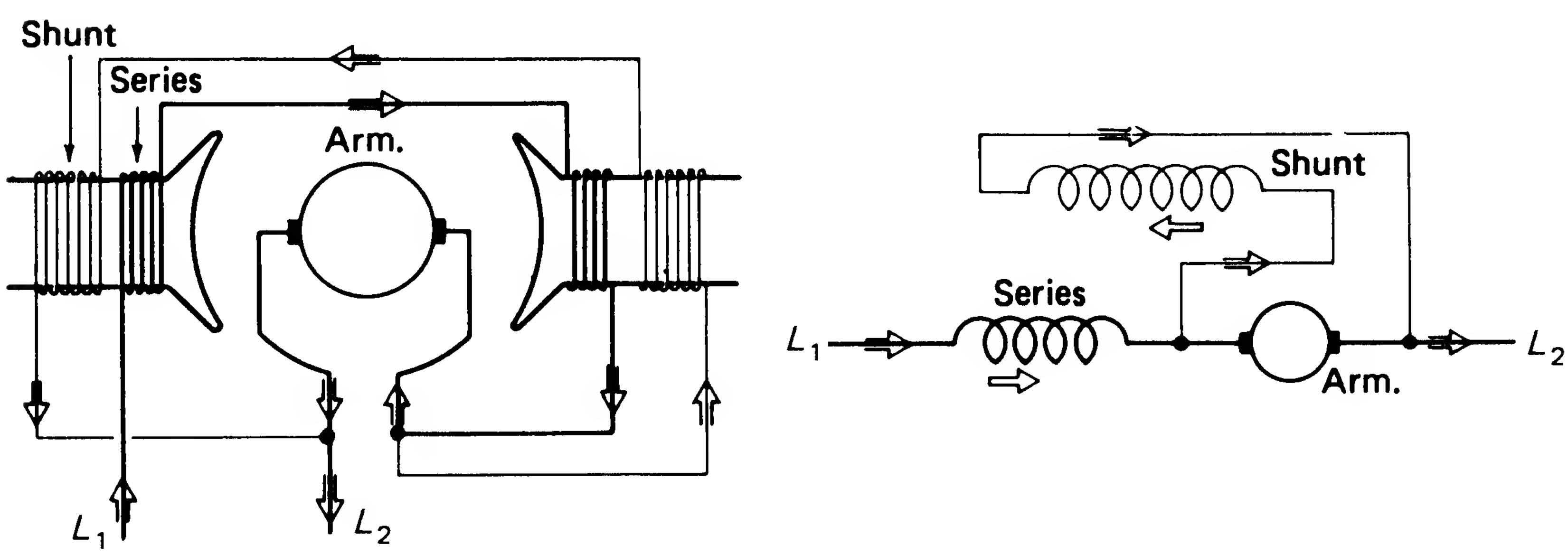


Fig. 6–35. A two-pole, short-shunt differentially compounded motor.

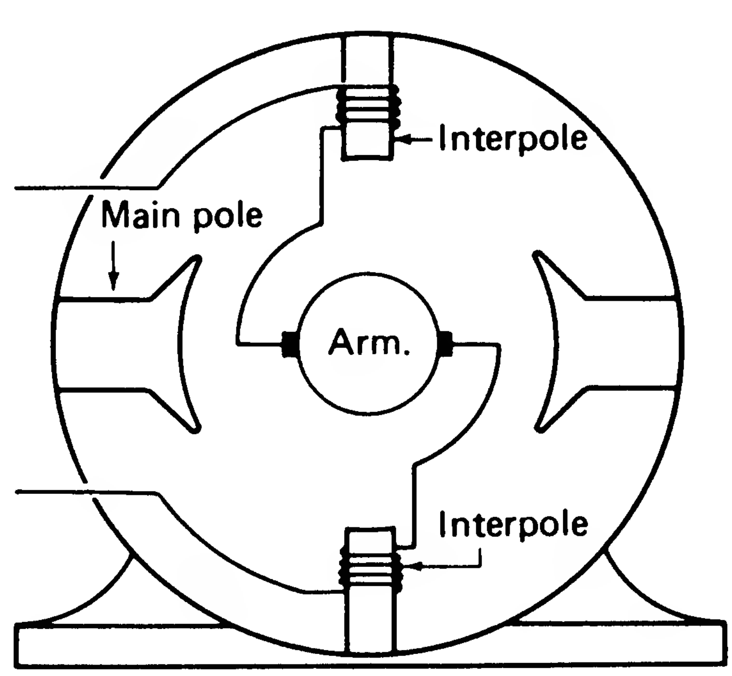


Fig. 6–36. Method of connecting the interpole in a two-pole motor.

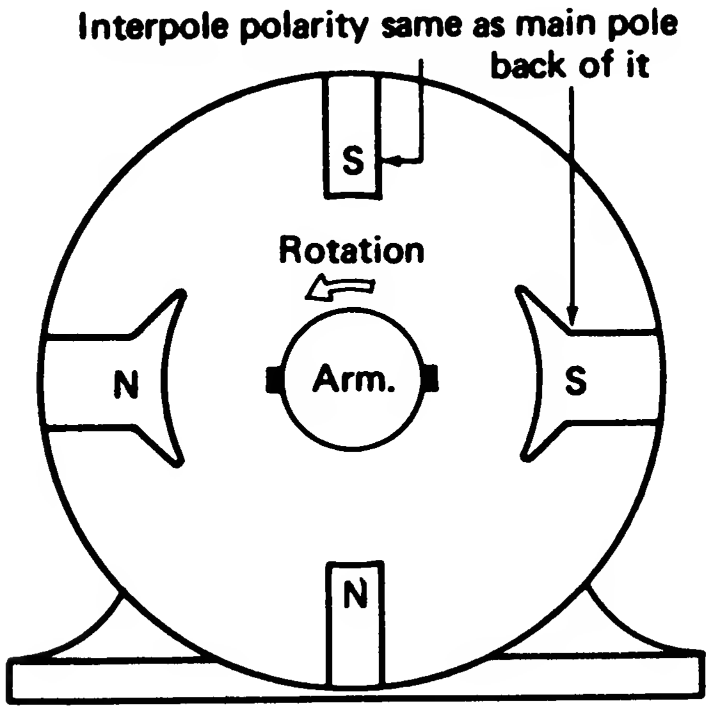


Fig. 6-37. The polarity of the interpole for counterclockwise (c.c.w.) rotation of a two-pole motor.

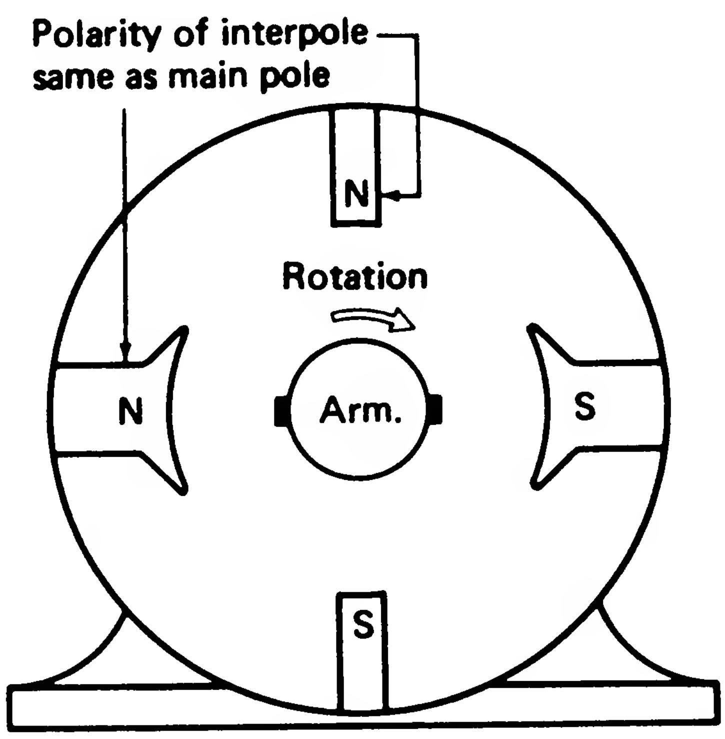


Fig. 6-38. The proper interpole polarity for clockwise (c.w.) rotation of a two-pole motor.

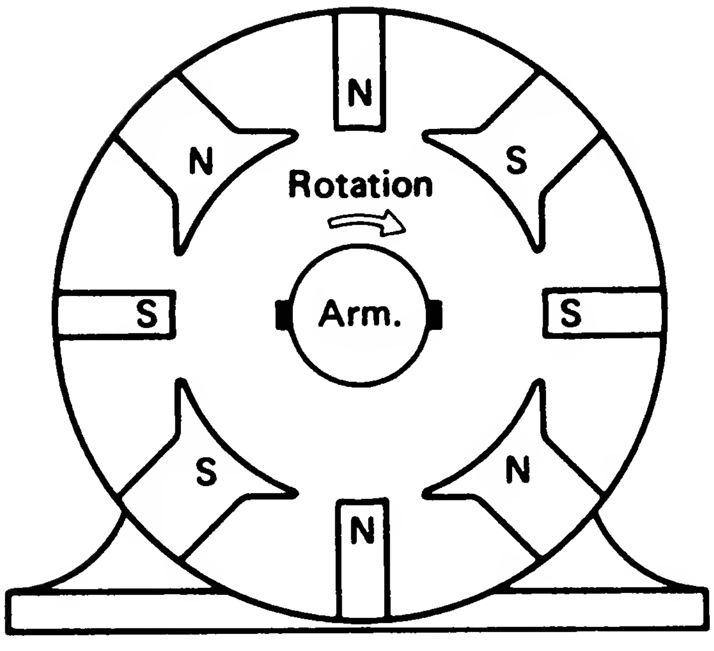


Fig. 6-39. The polarity of the interpole for clockwise (c.w.) rotation of a four-pole motor.

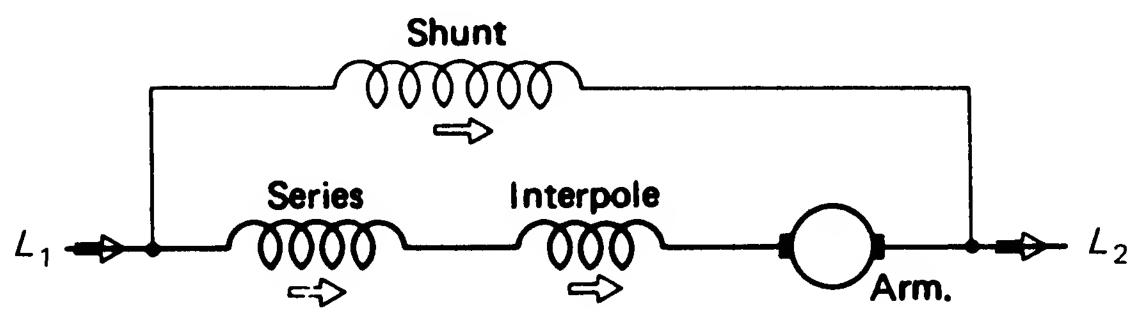


Fig. 6–40. A schematic diagram of a compound-interpole motor.

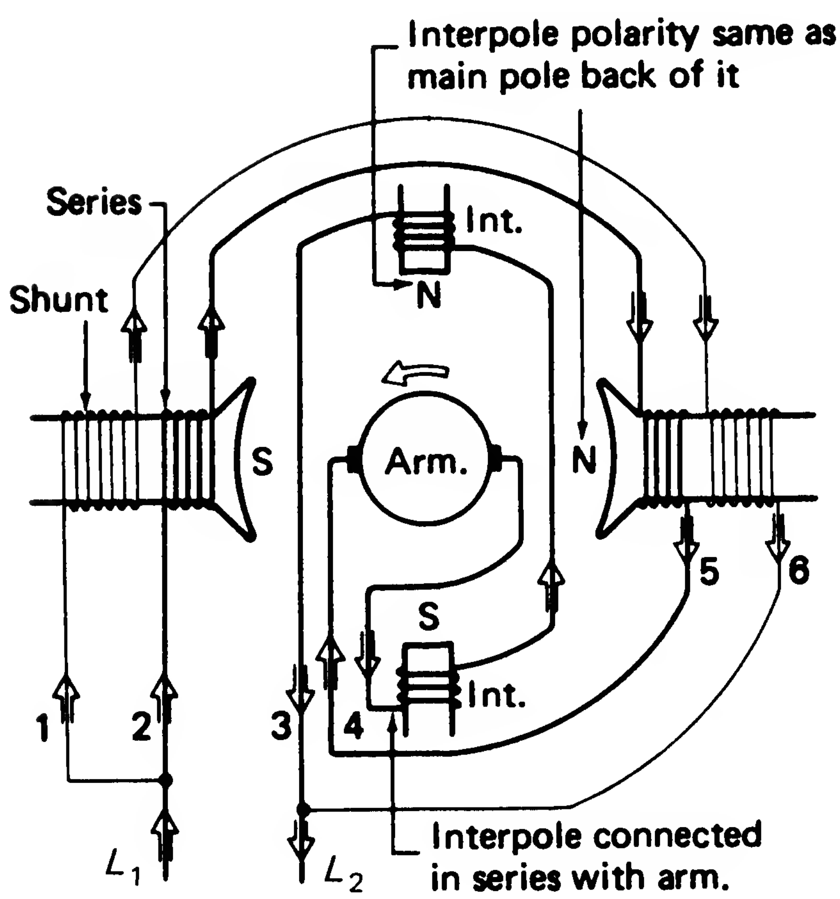


Fig. 6–41. A two-pole compound-interpole motor. With the polarity indicated, the motor will run counterclockwise.

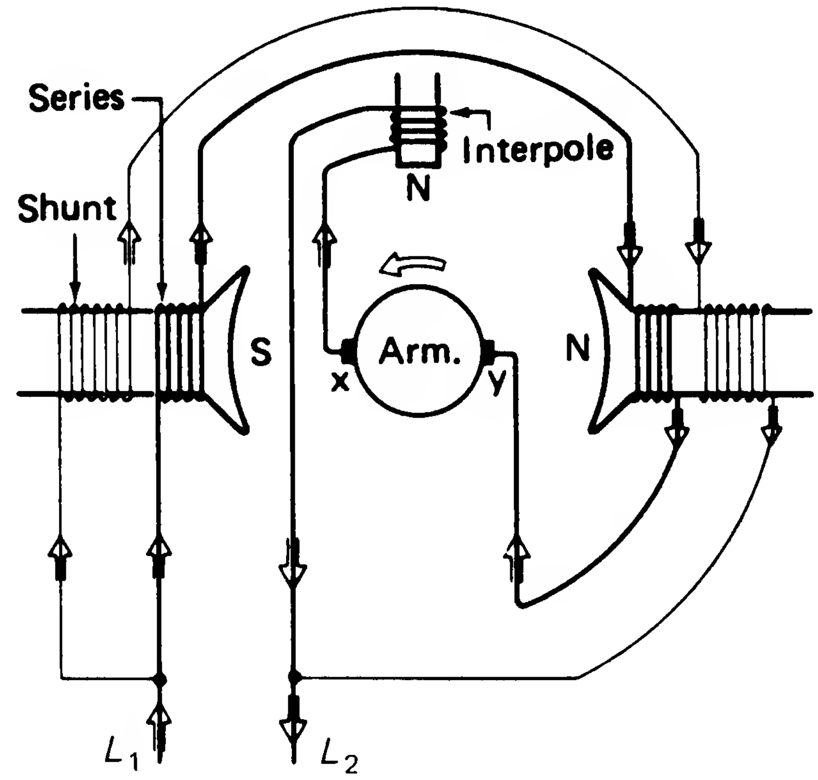


Fig. 6–42. A two-pole compound-interpole motor using one interpole connected in series with the armature.

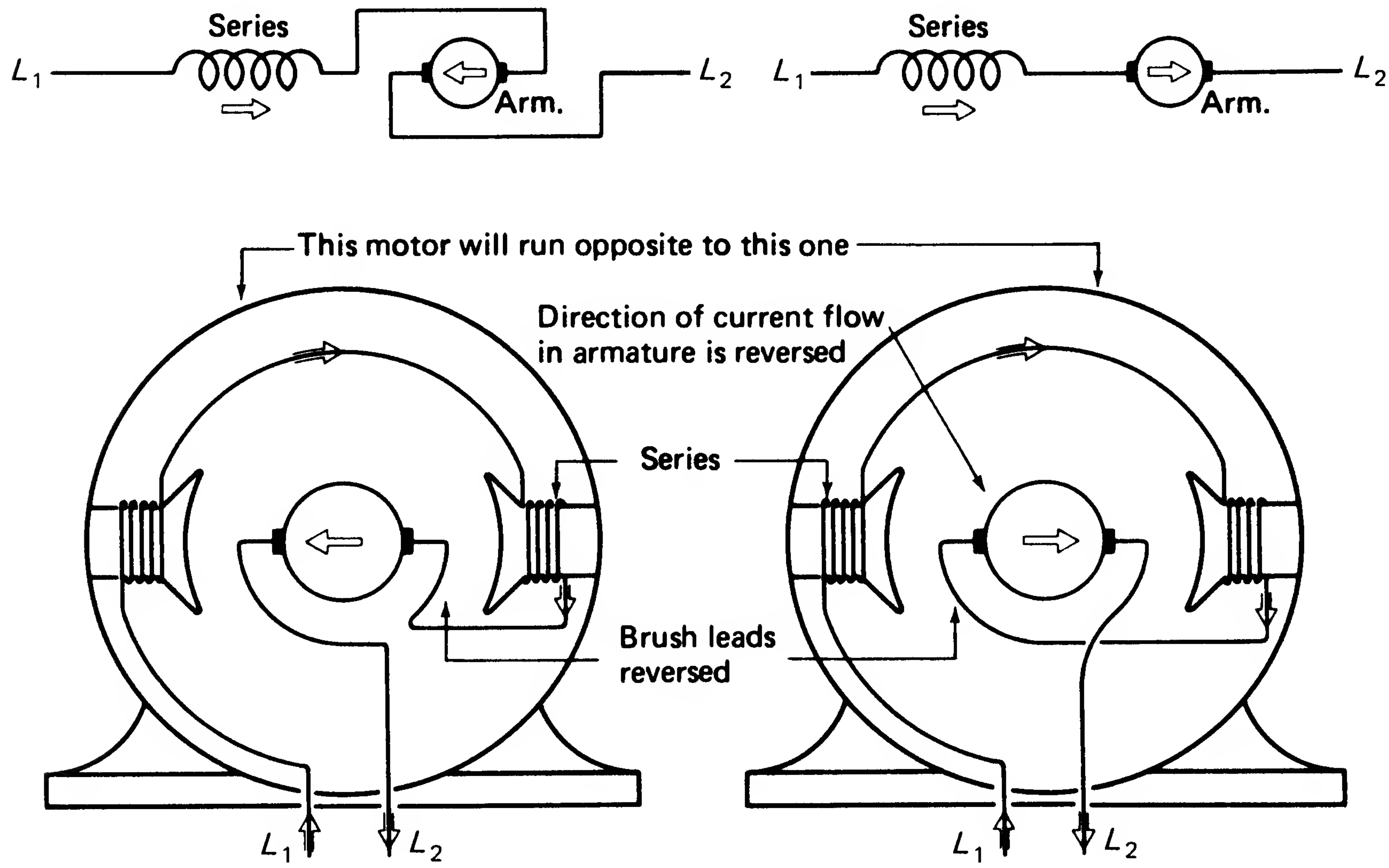


Fig. 6–43. The direction of rotation of a two-pole series motor changed by reversing the current flow in the armature.

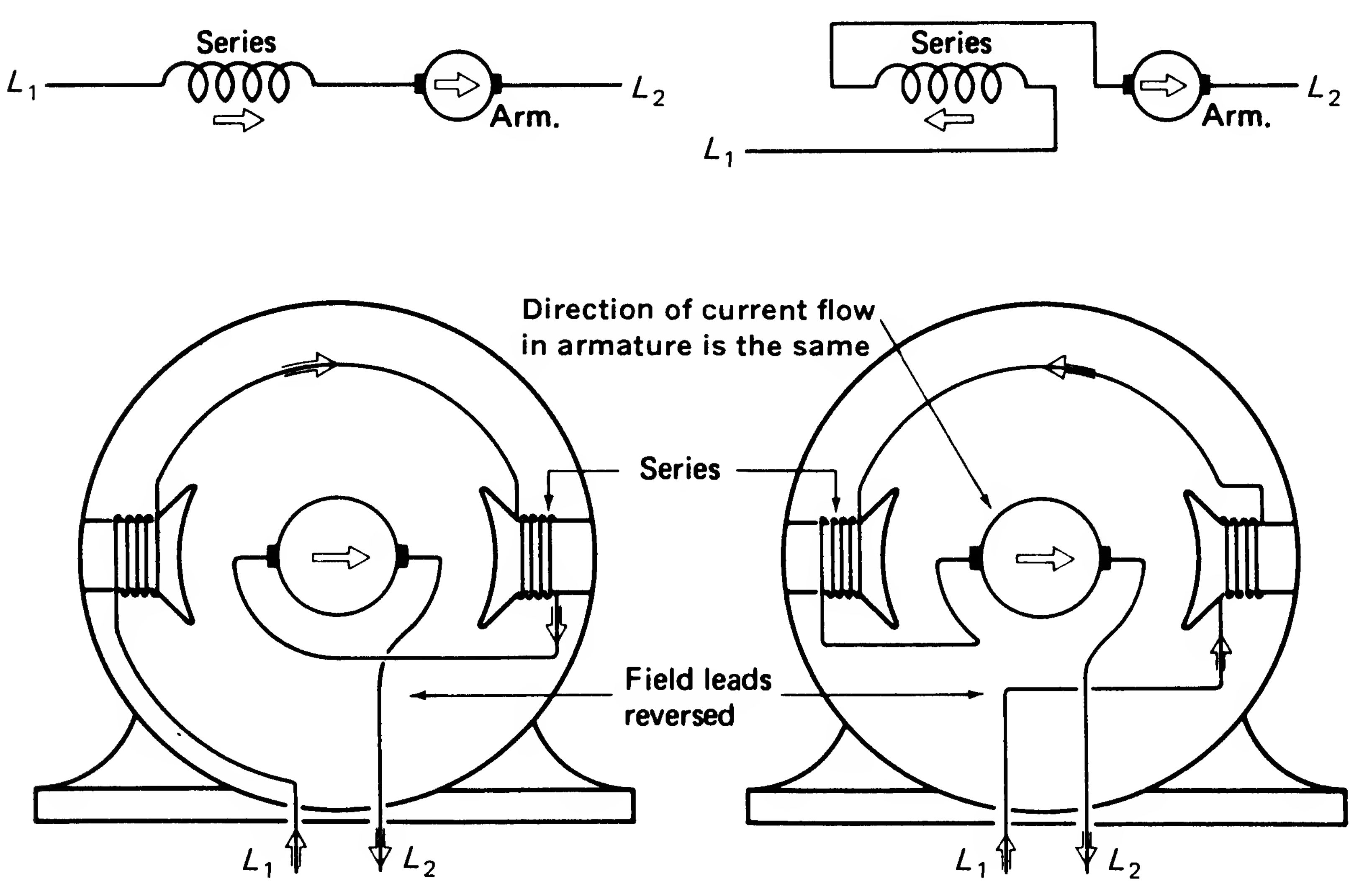


Fig. 6–44. The direction of rotation of a two-pole series motor changed by reversing the current flow in the field poles.

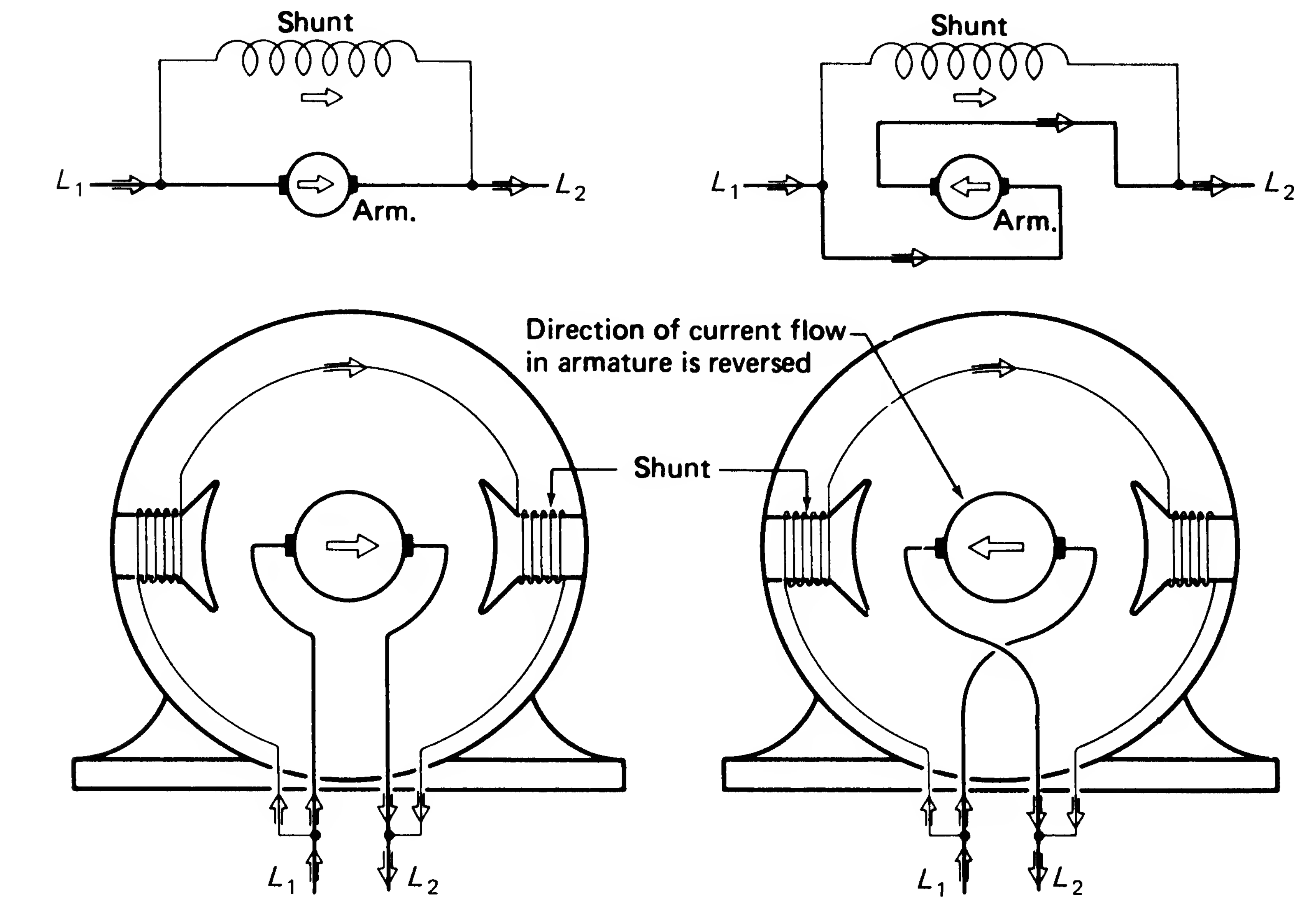


Fig. 6–45. A two-pole shunt motor reversed in the armature circuit.

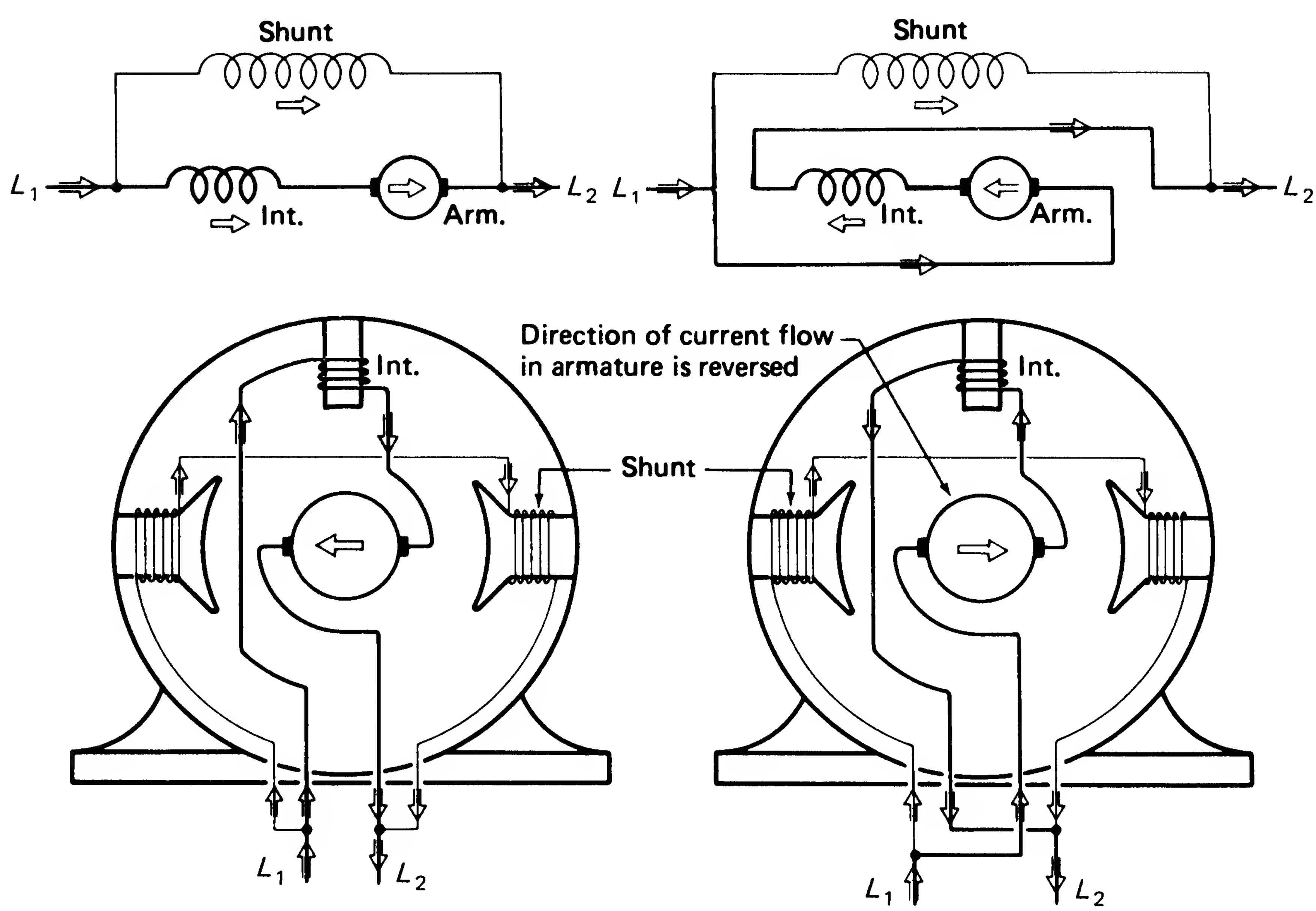


Fig. 6–46. A two-pole shunt-interpole motor. The armature and interpole leads are reversed as a unit. The field polarity remains the same.

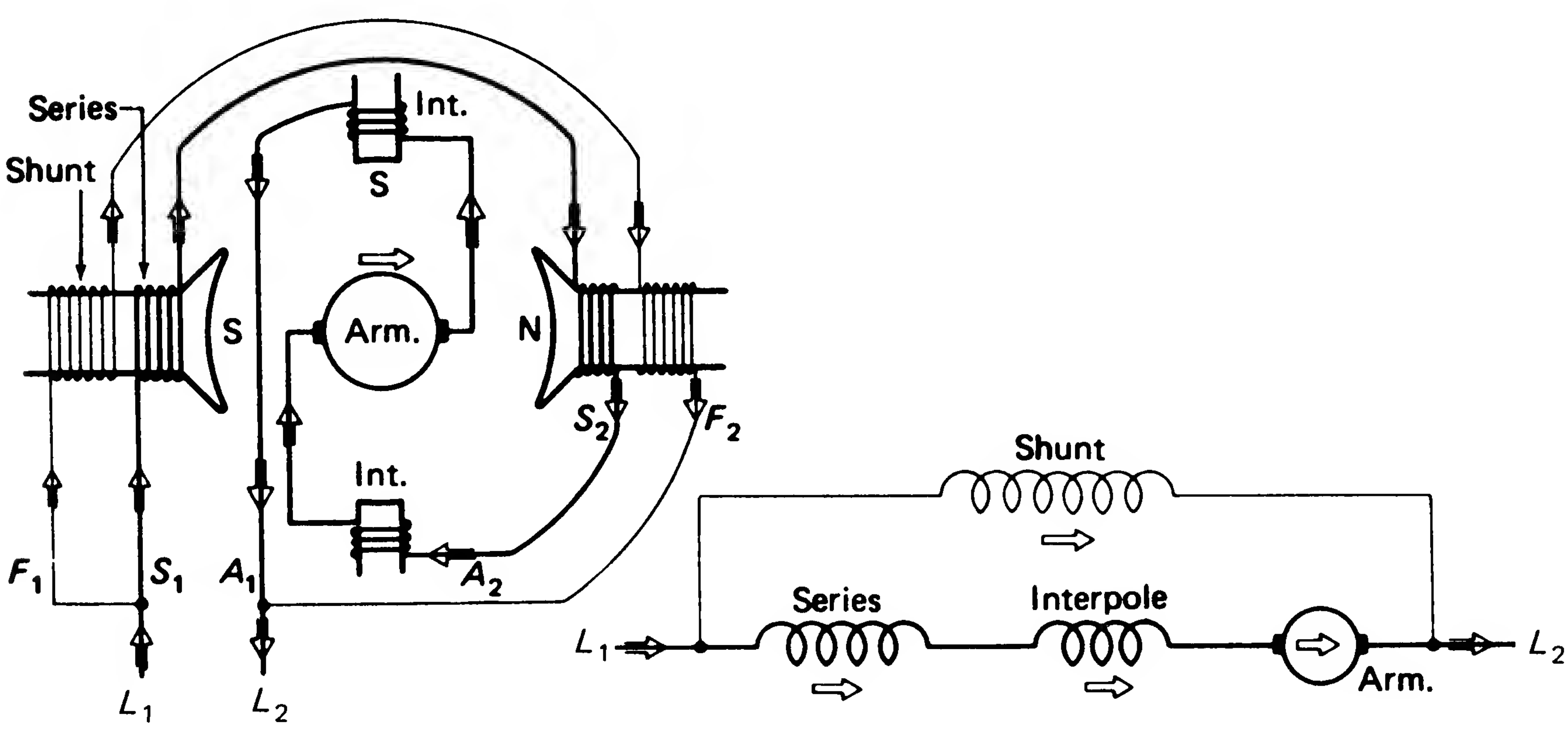


Fig. 6–47. A two-pole compound-interpole motor with six wires brought out of the motor. Wires F_1 and S_1 are sometimes connected together inside the motor, and one wire is brought outside.

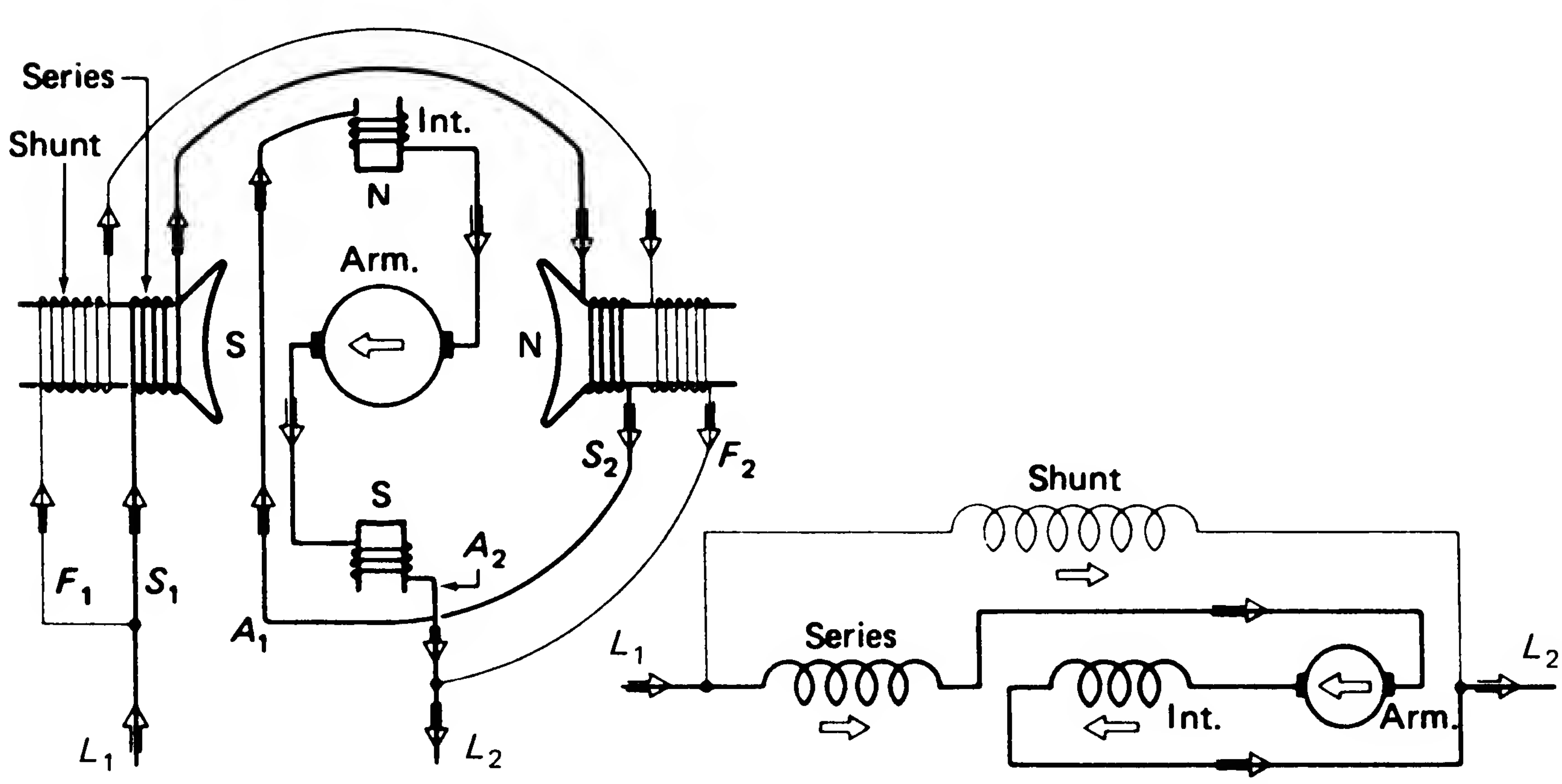


Fig. 6–48. A two-pole compound-interpole motor with the armature circuit reversed for opposite rotation from that of **Fig. 6–47**.

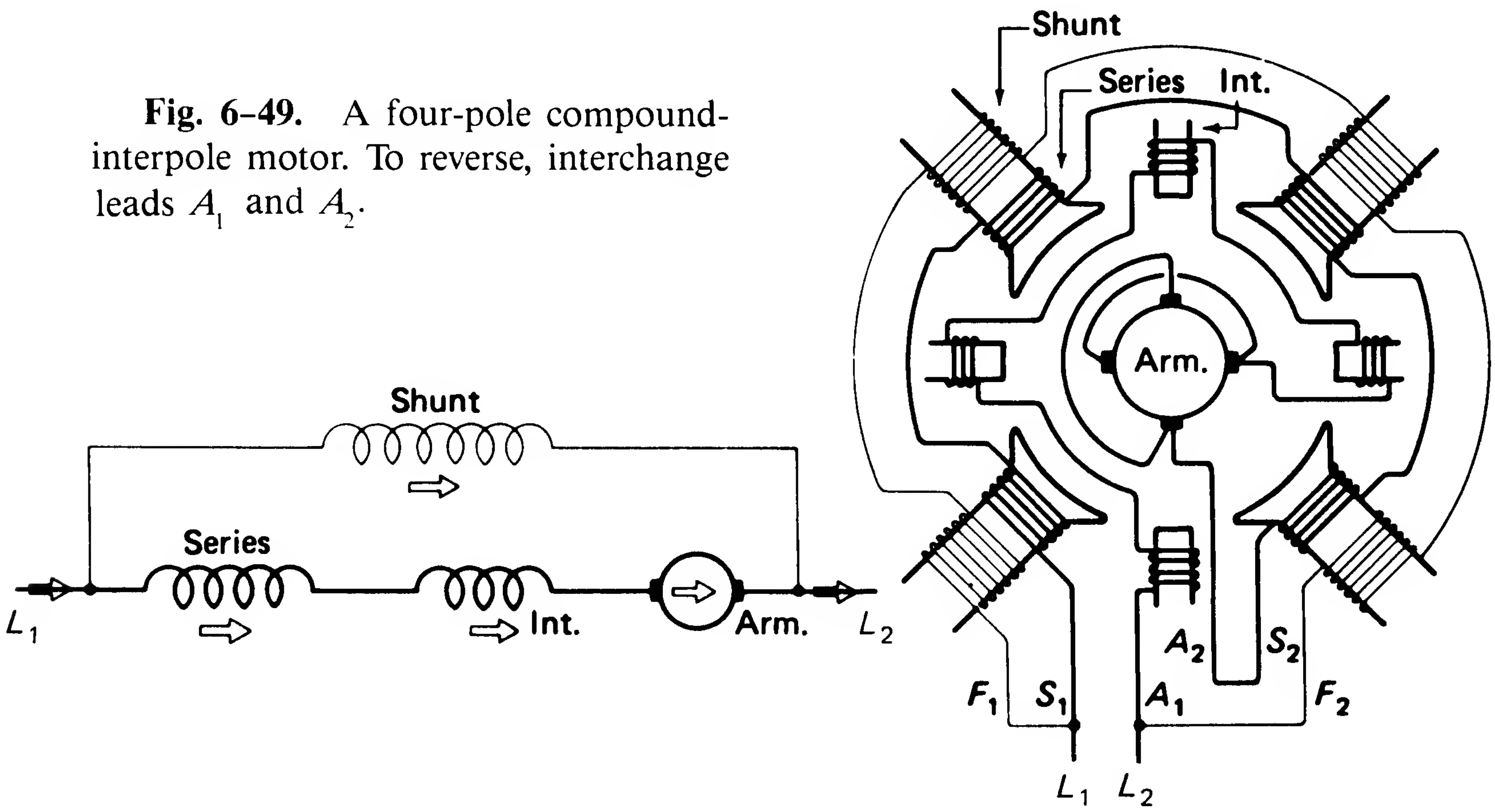


Fig. 6-49. A four-pole compound-interpole motor. To reverse, interchange leads A_1 and A_2.

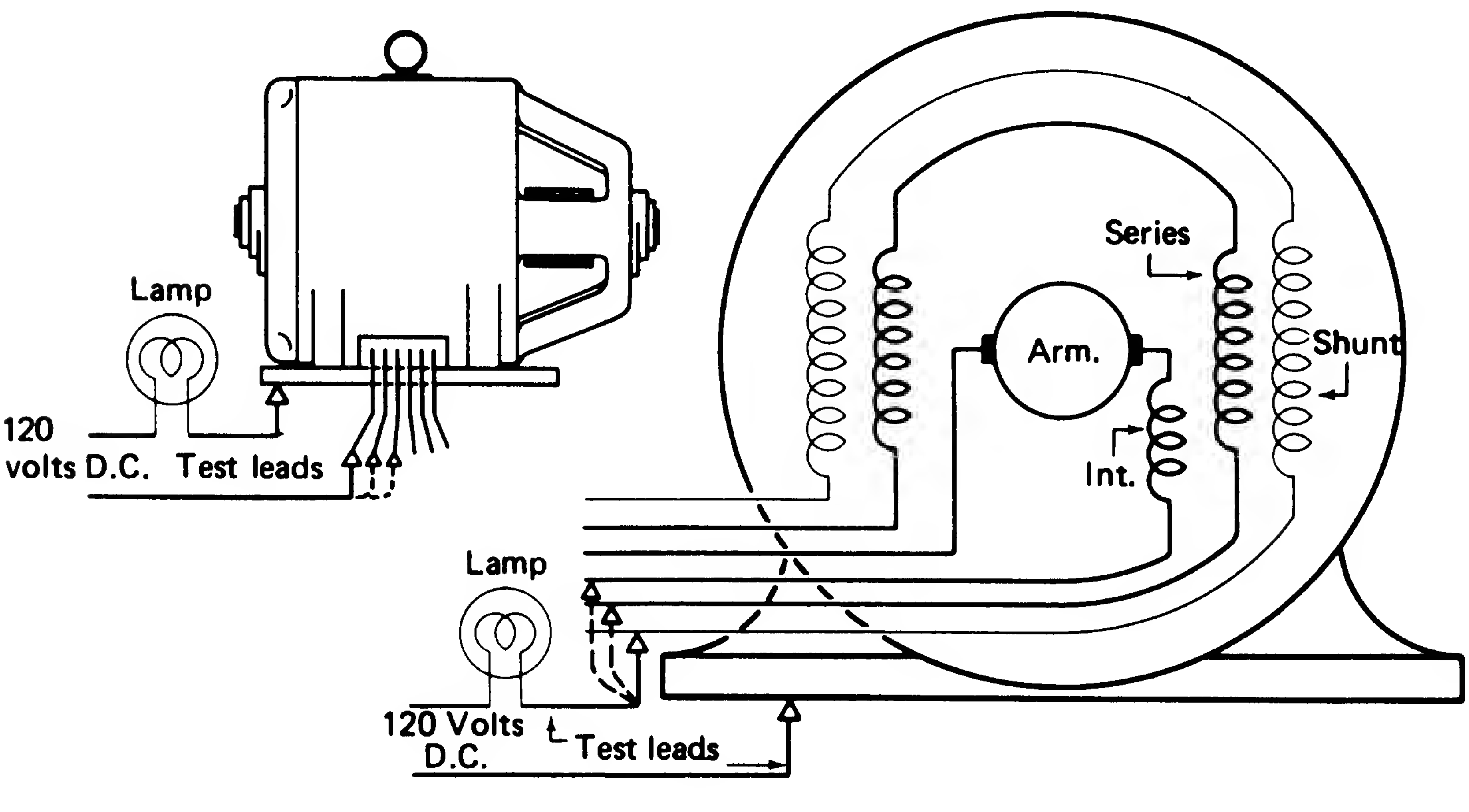


Fig. 6-50. Testing a compound motor for grounds.

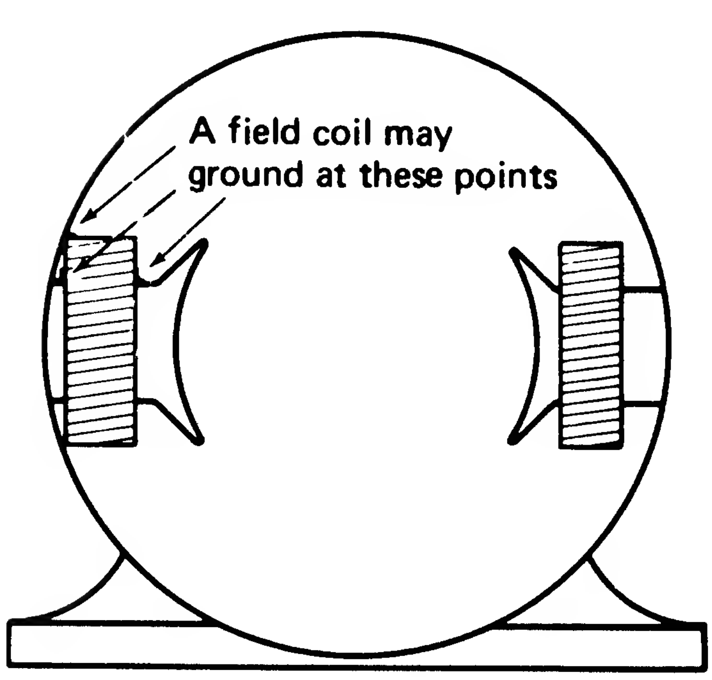


Fig. 6-51. The positions where the field most often grounds.

Fig. 6–52a. To locate the grounded field coil, each coil is given a ground test.

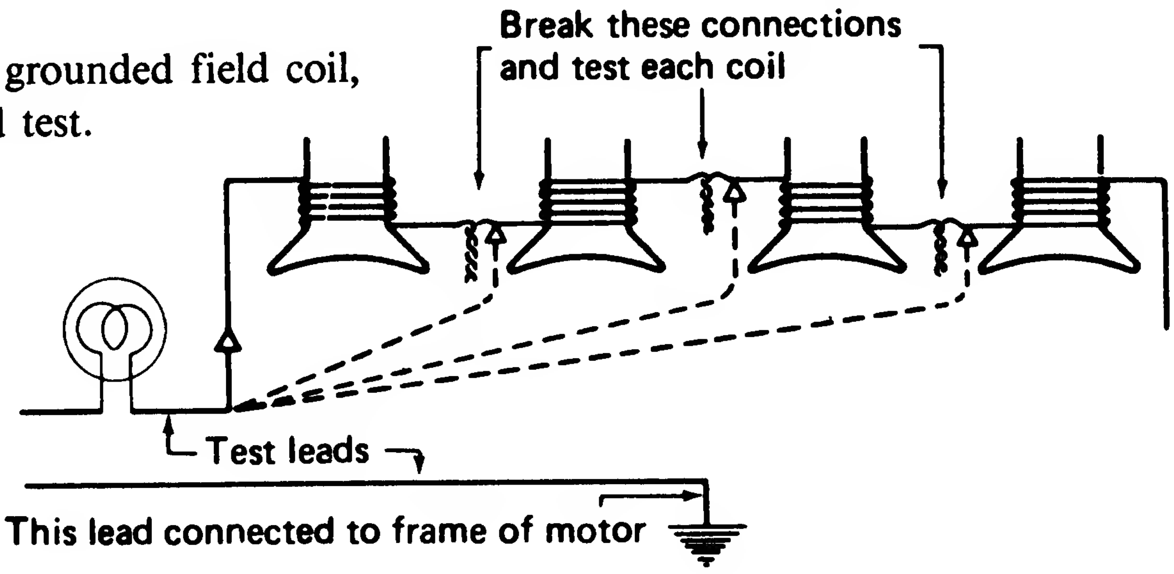
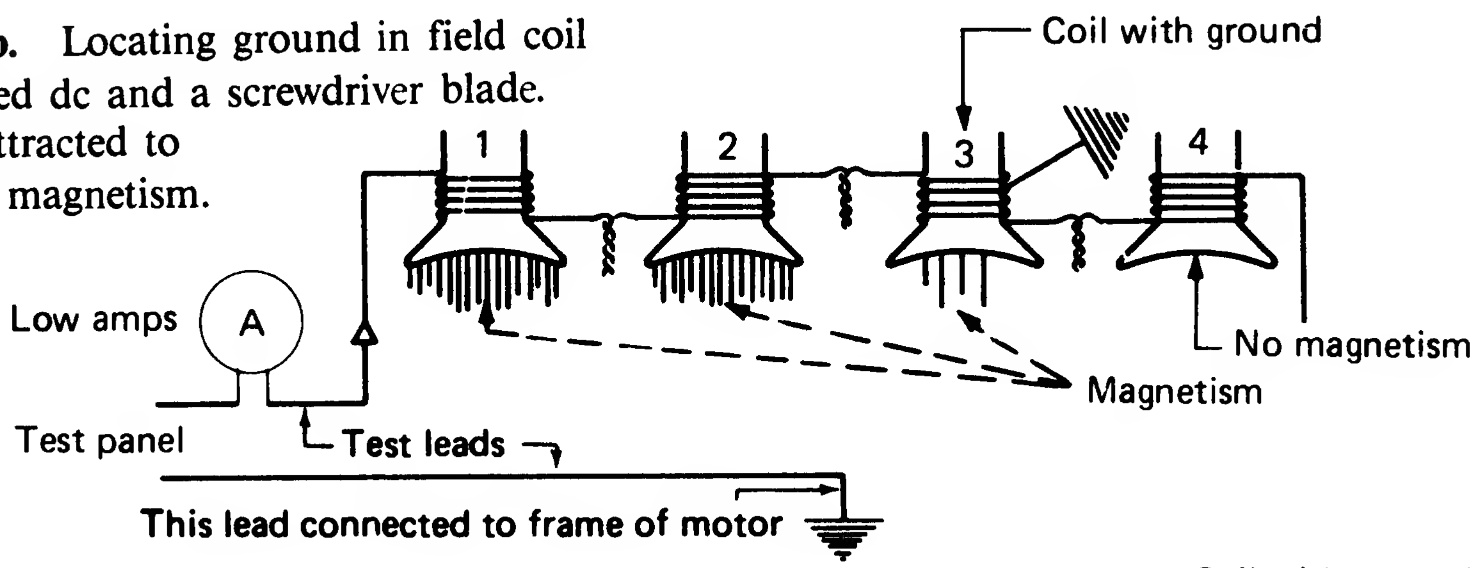


Fig. 6–52b. Locating ground in field coil with limited dc and a screwdriver blade. Blade is attracted to coils with magnetism.



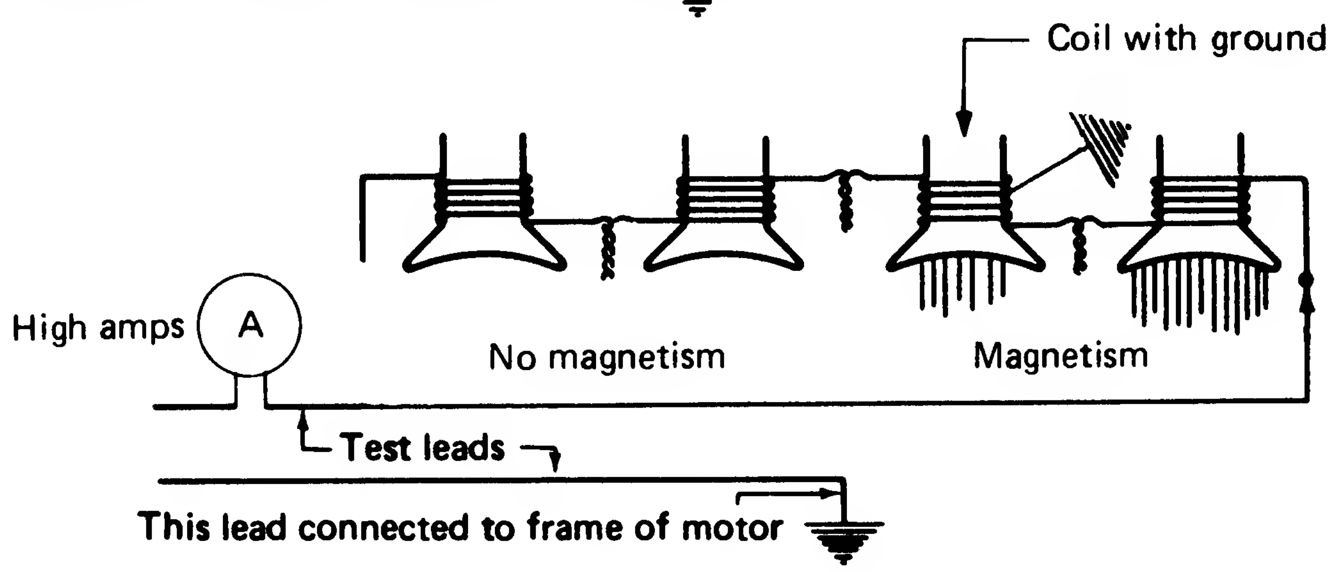
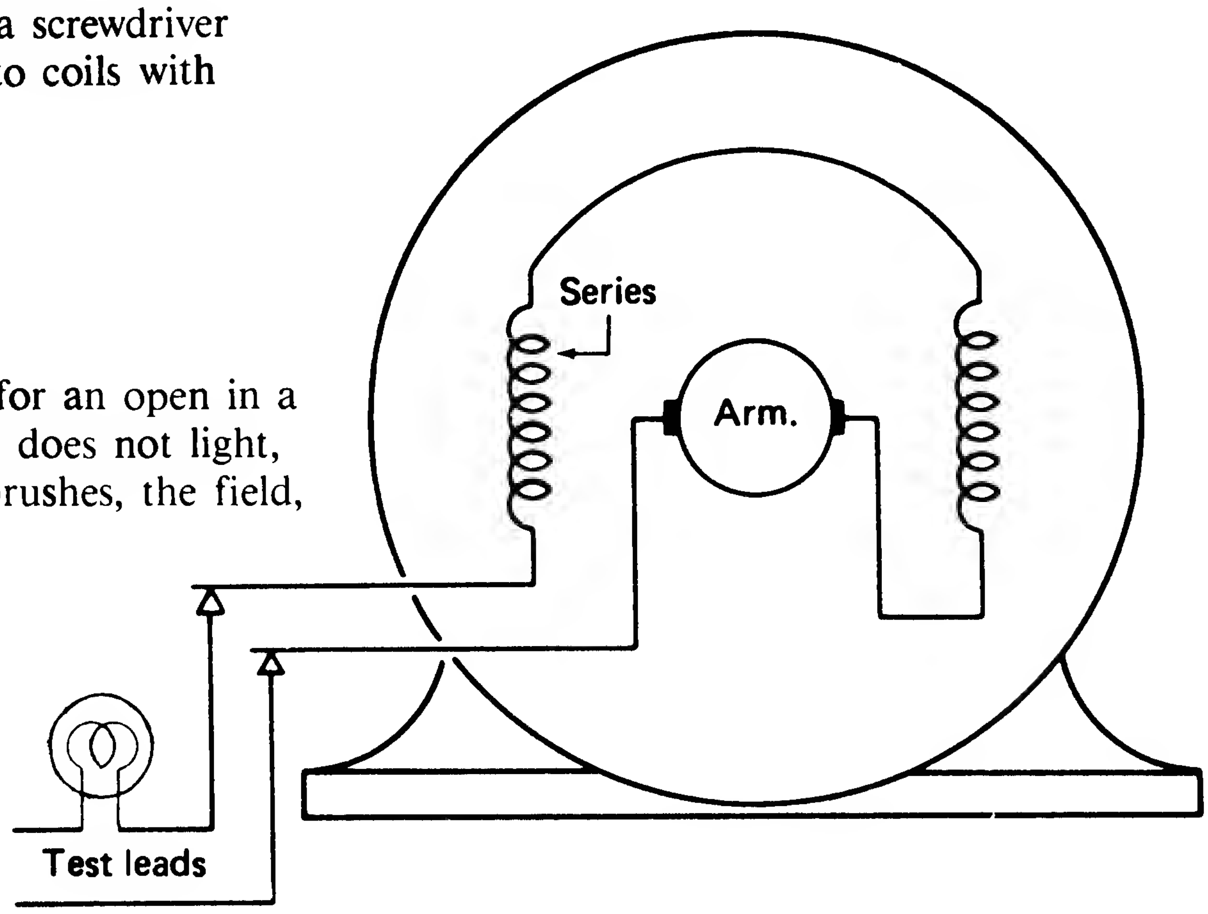


Fig. 6–52c. Locating ground in field coil with limited current and a screwdriver blade. Blade is attracted to coils with magnetism.

Fig. 6–53. The test for an open in a series motor. If the lamp does not light, the trouble may be the brushes, the field, or the connections.



Figures 6–52; 6–52a; 6–52b; 6–52c; 6–53

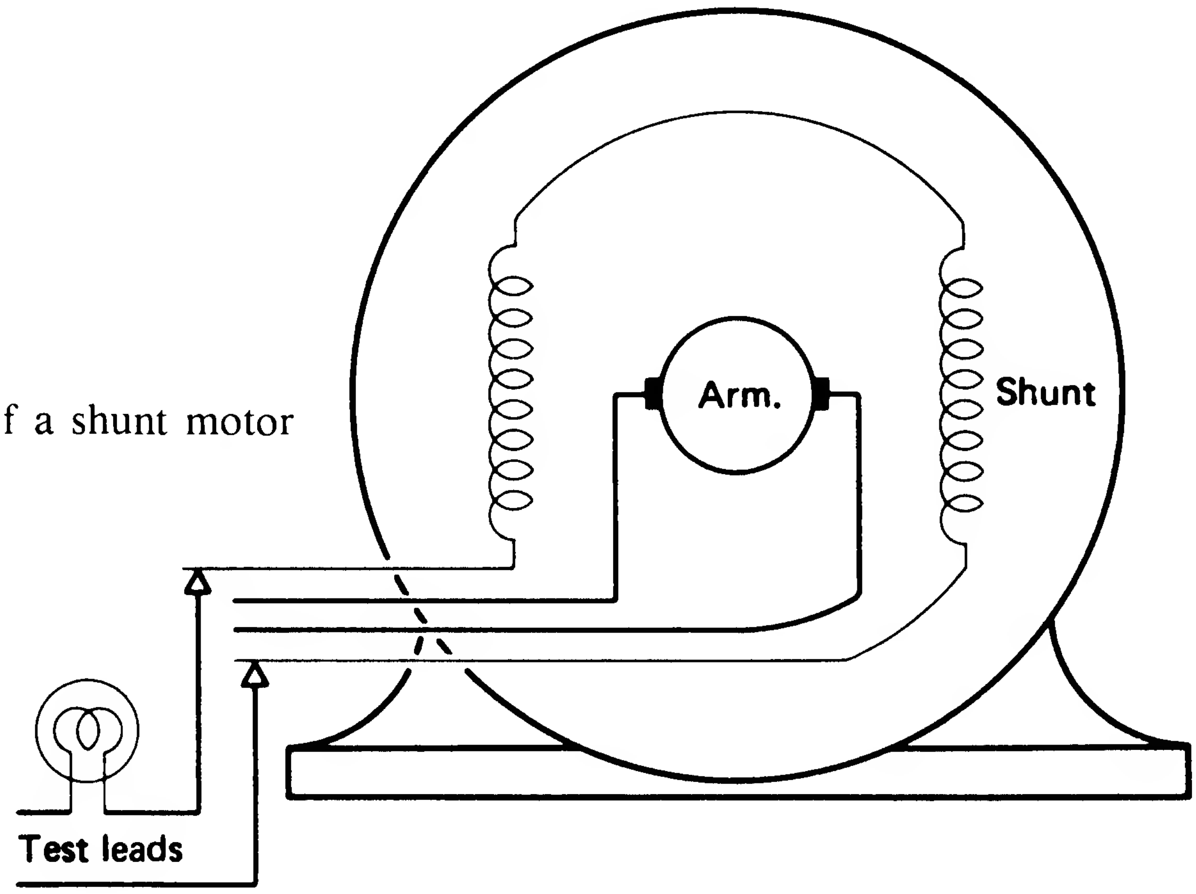


Fig. 6–54. The test of a shunt motor for opens.

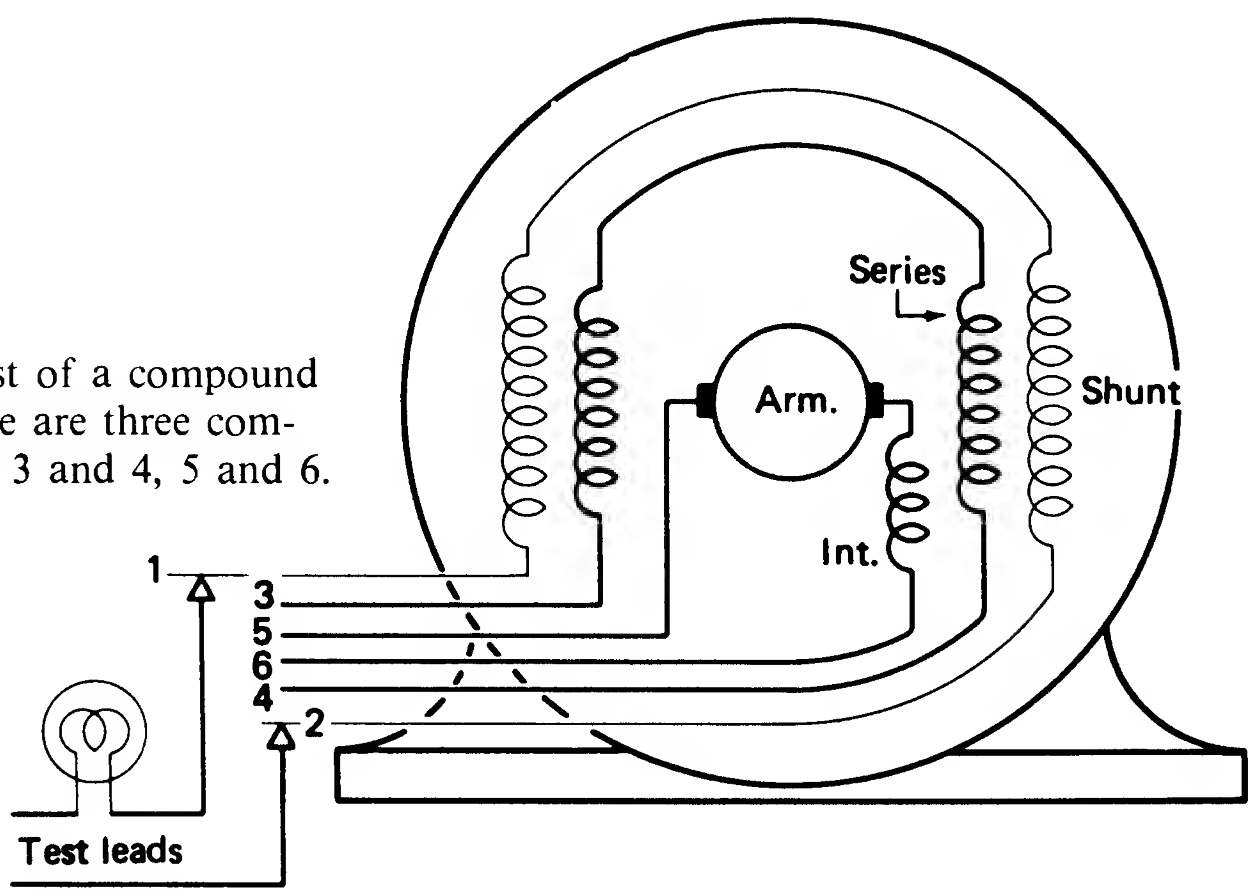


Fig. 6–55. The test of a compound motor for opens. There are three complete circuits: 1 and 2, 3 and 4, 5 and 6.

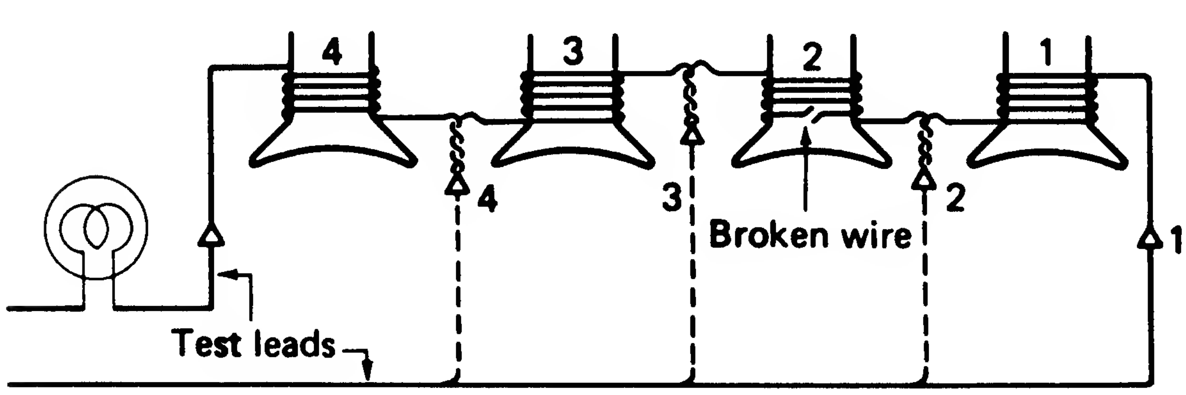


Fig. 6–56. The test for locating an open field coil in a four-pole motor.

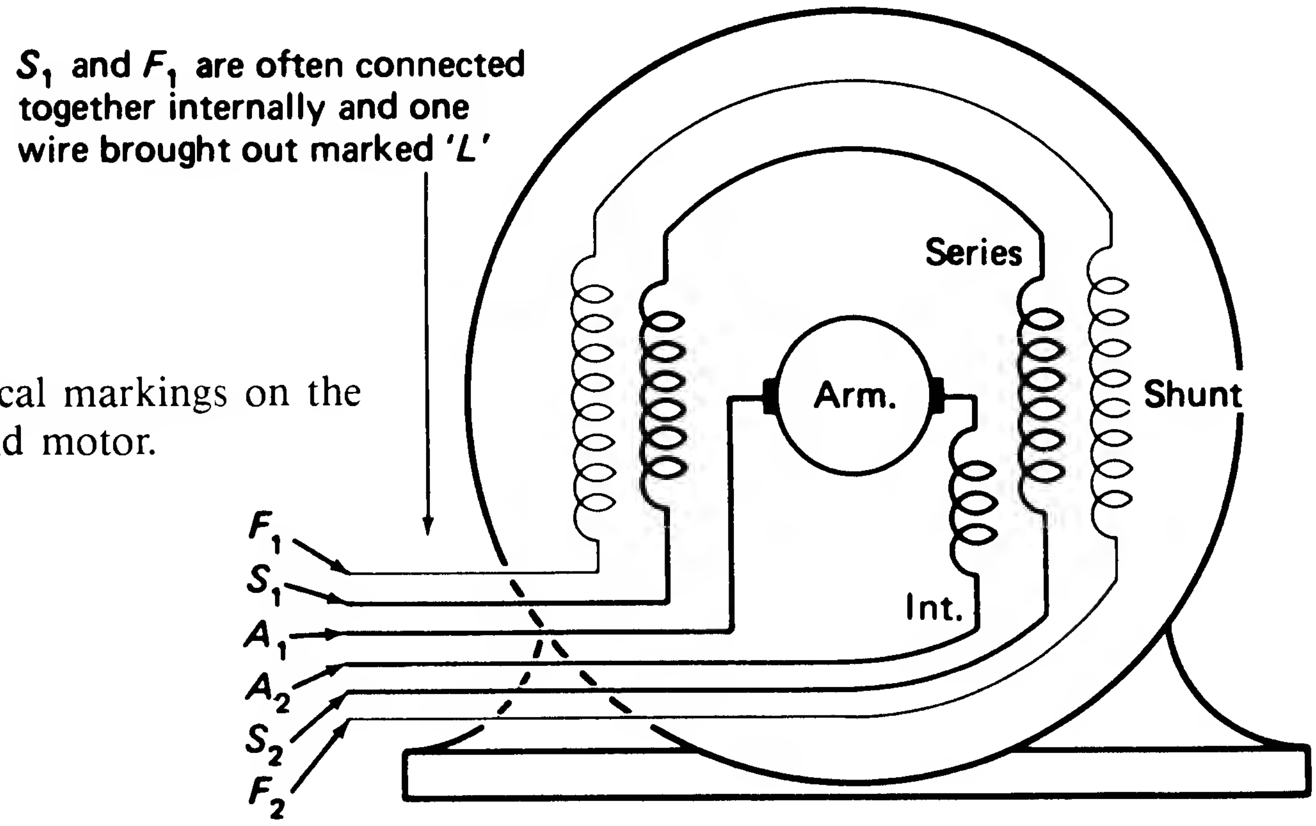


Fig. 6–57. Typical markings on the leads of a compound motor.

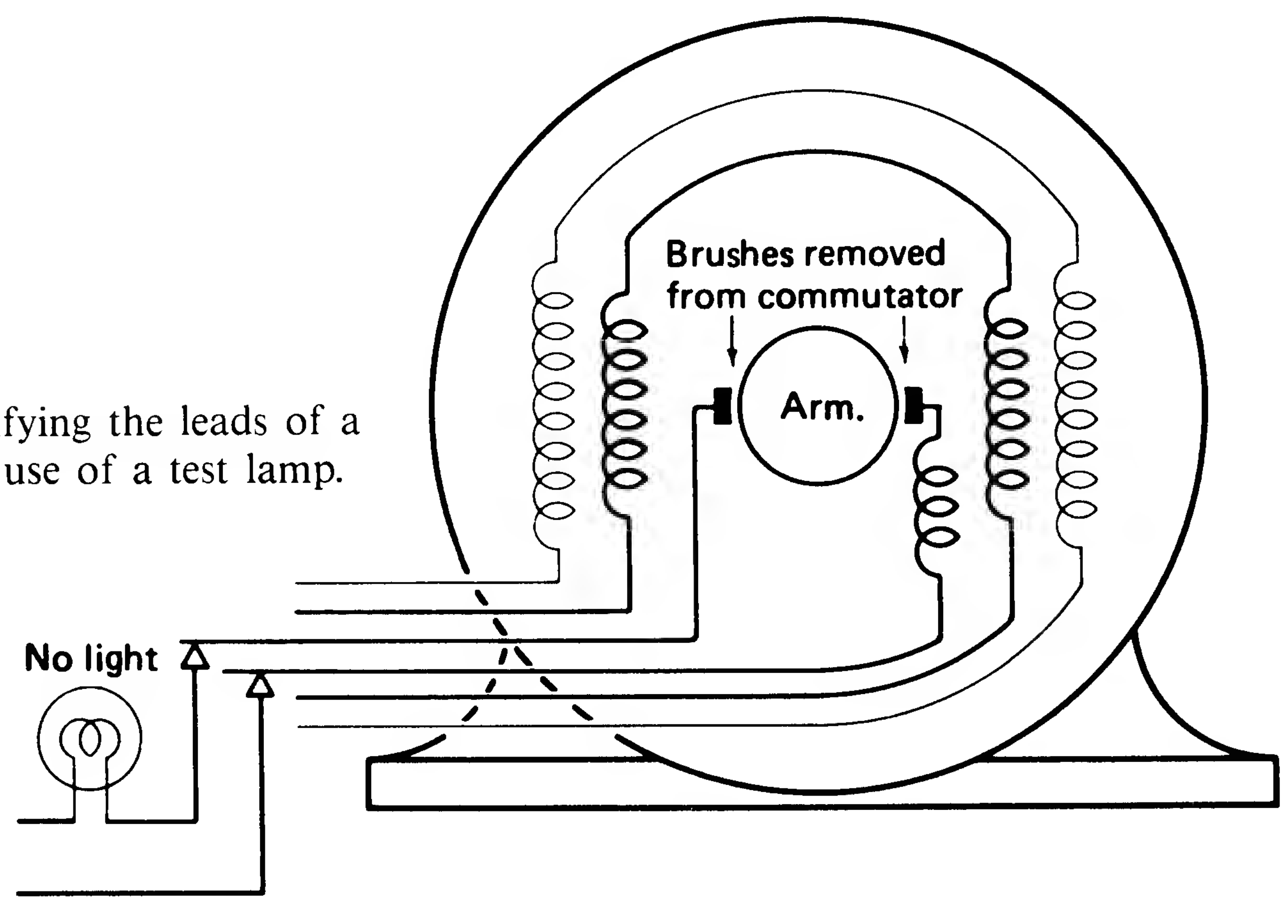


Fig. 6–58. Identifying the leads of a compound motor by use of a test lamp.

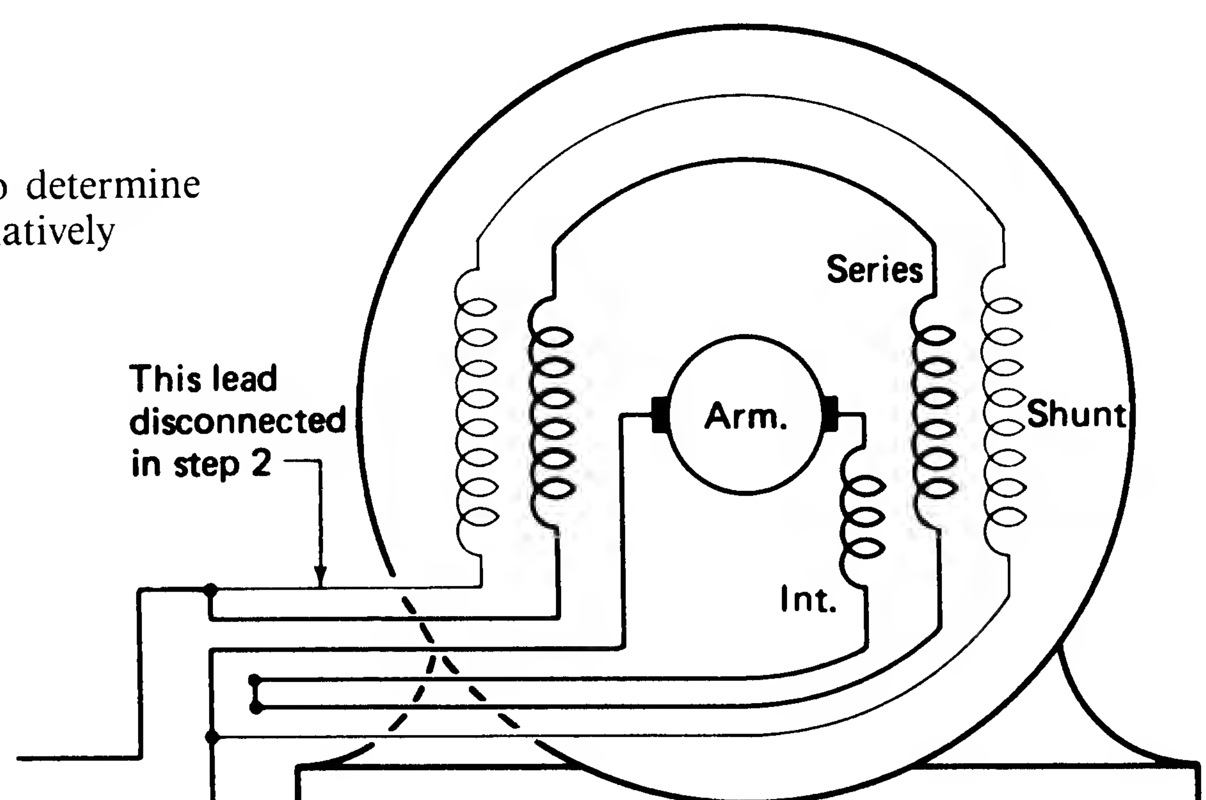


Fig. 6–59. The test to determine whether a motor is cumulatively connected.

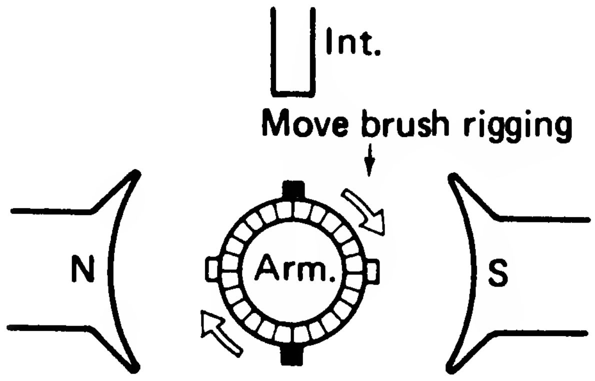
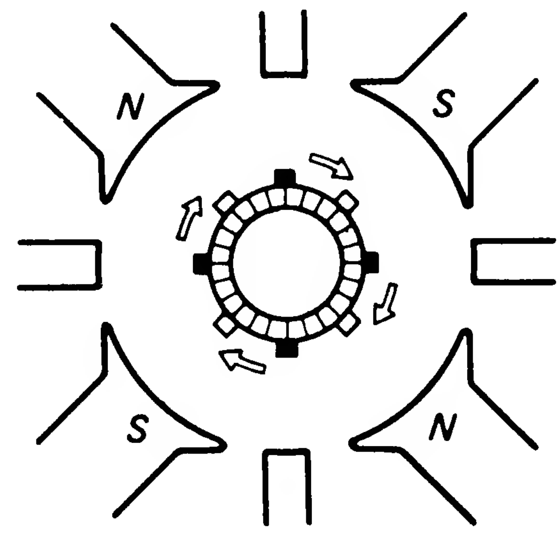


Fig. 6-60. The test for interpole polarity in a two-pole motor. All connections are removed except the armature and interpole. The brushes are shifted 90 degrees, and if the armature turns in the same direction in which the brushes were moved, the polarity is correct.

Fig. 6-61. The test for correct interpole polarity in a four-pole motor.



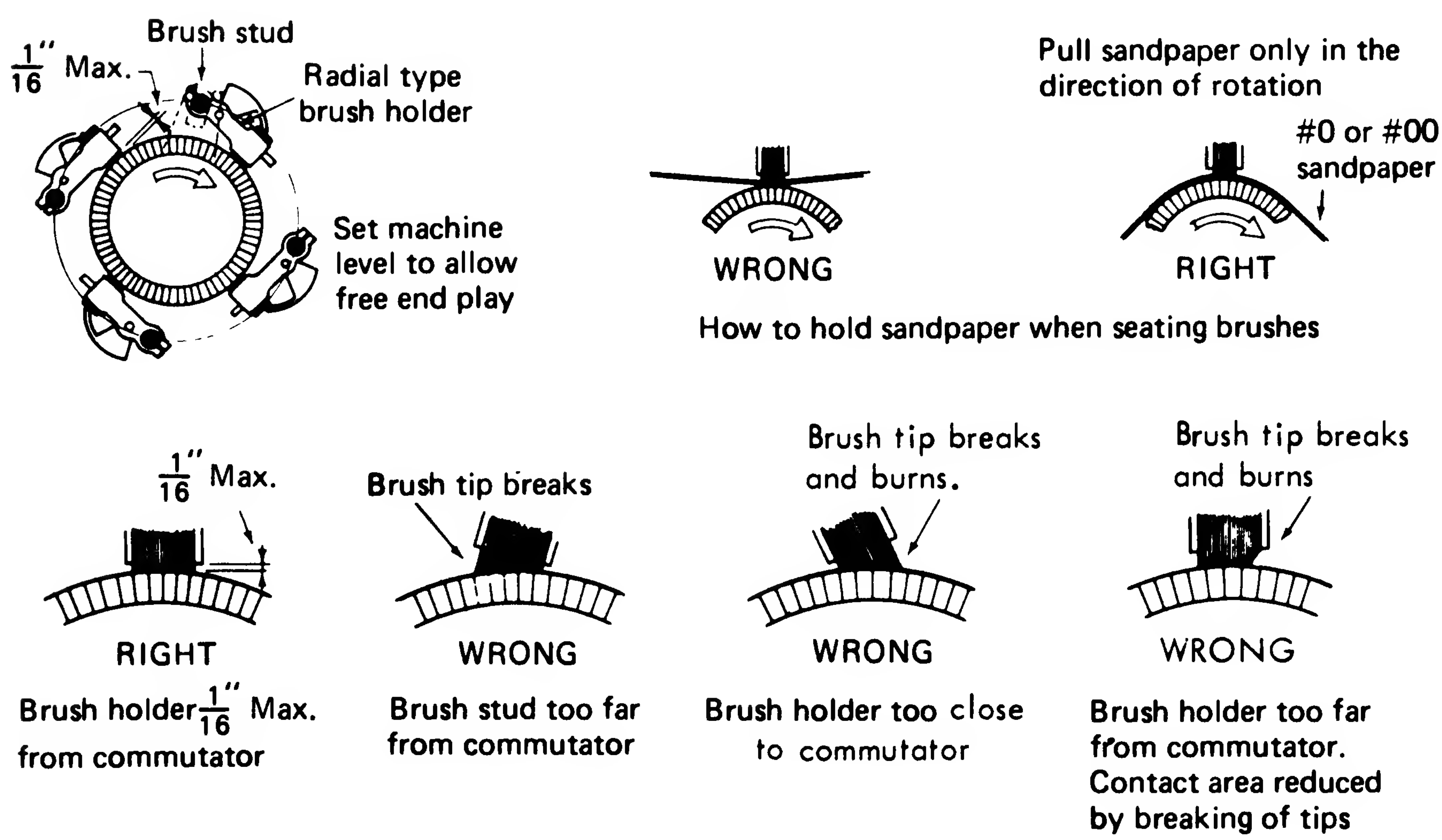


Fig. 6-62. The correct and incorrect positions of a carbon brush.

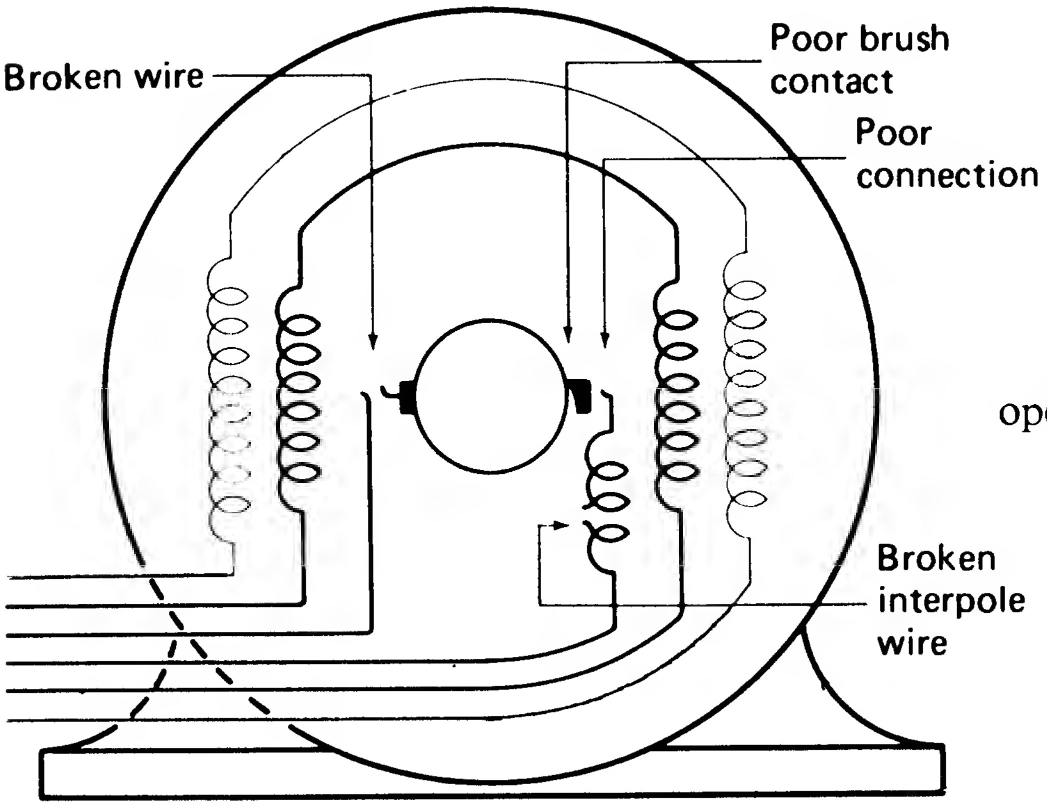
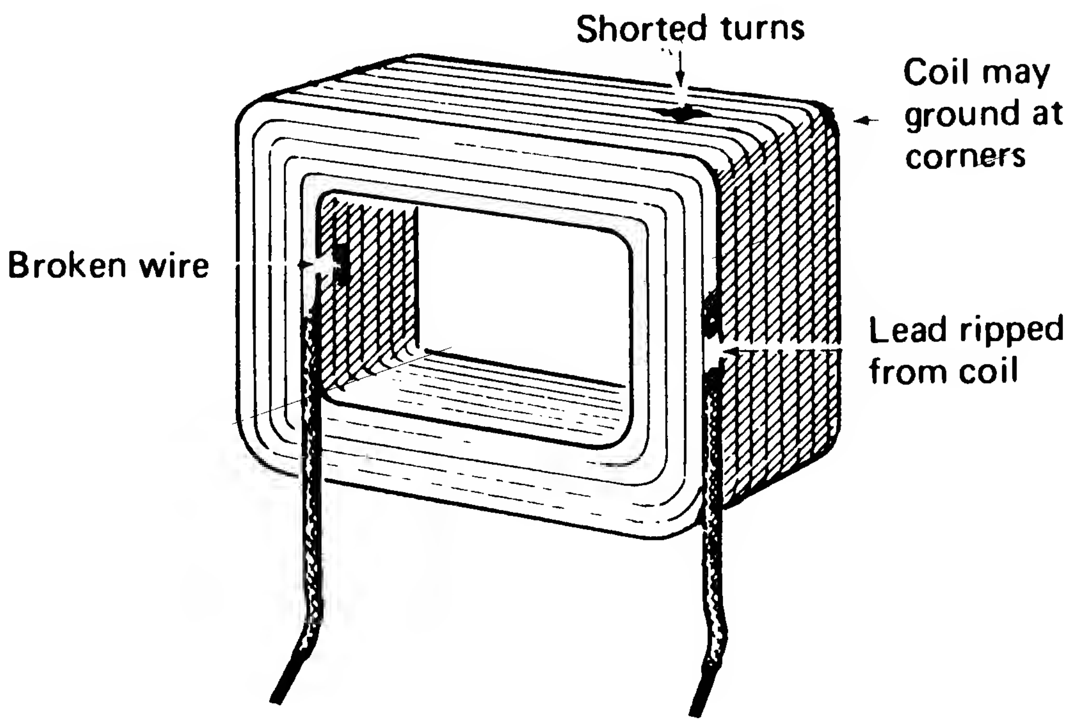


Fig. 6–63. Possible causes of an open armature circuit.



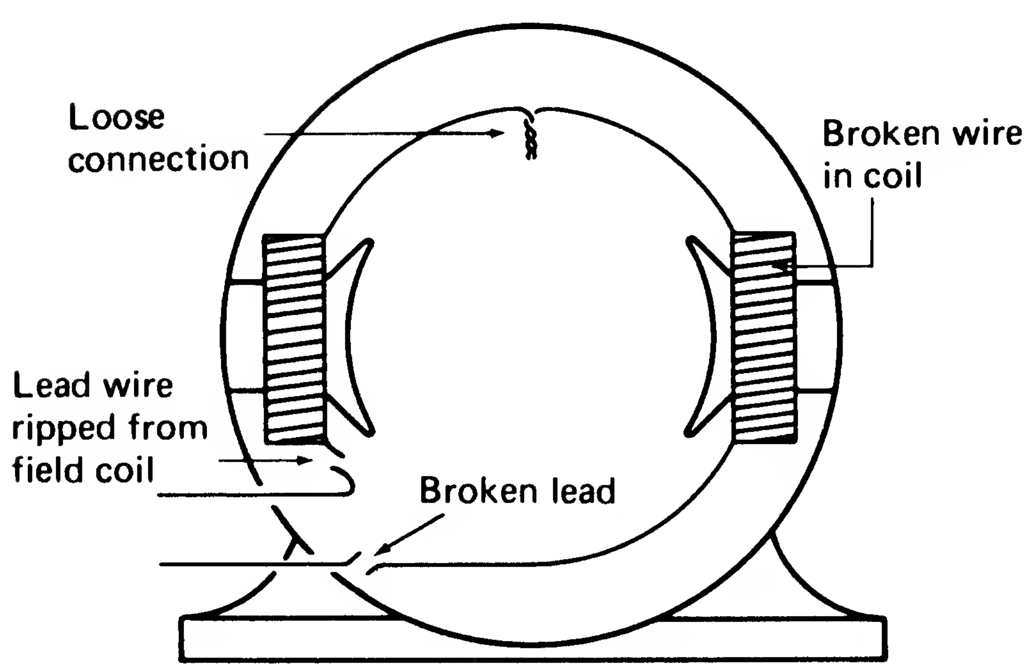


Fig. 6–64. Possible locations of opens in the field circuit and coil.

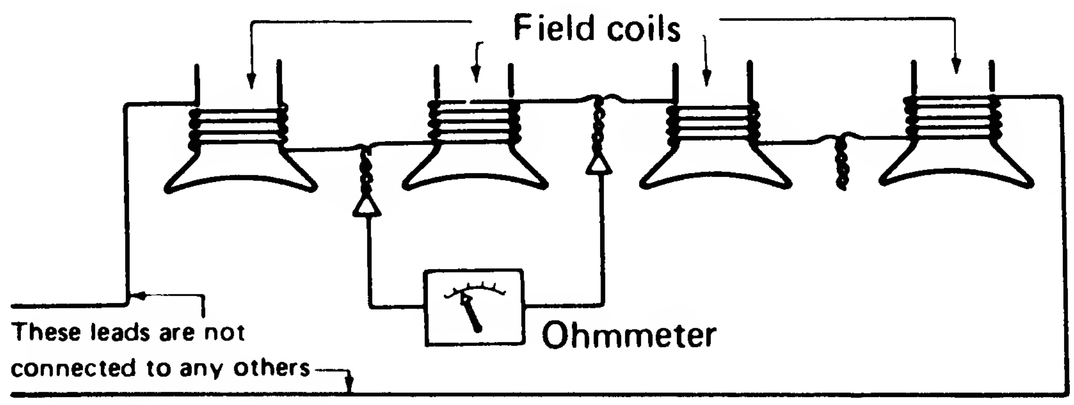


Fig. 6–65. The ohmmeter method of detecting a shorted coil.

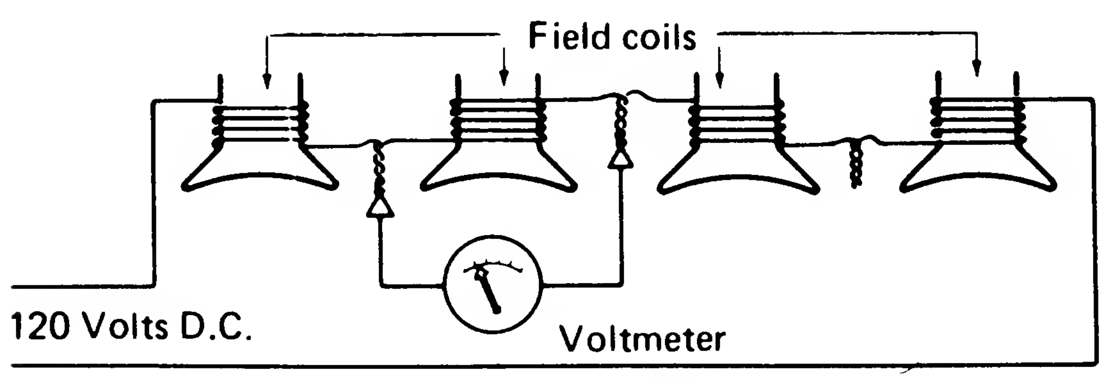


Fig. 6–66. The voltmeter method of locating a shorted coil.

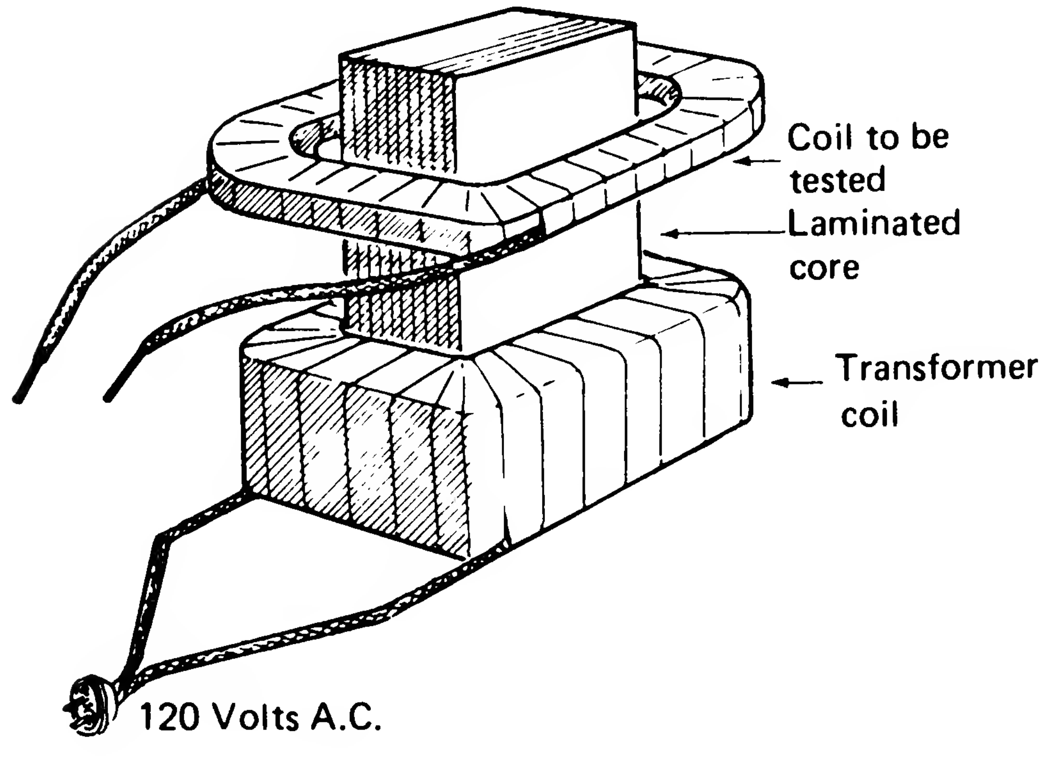


Fig. 6–67. A transformer used for testing shorted coils.

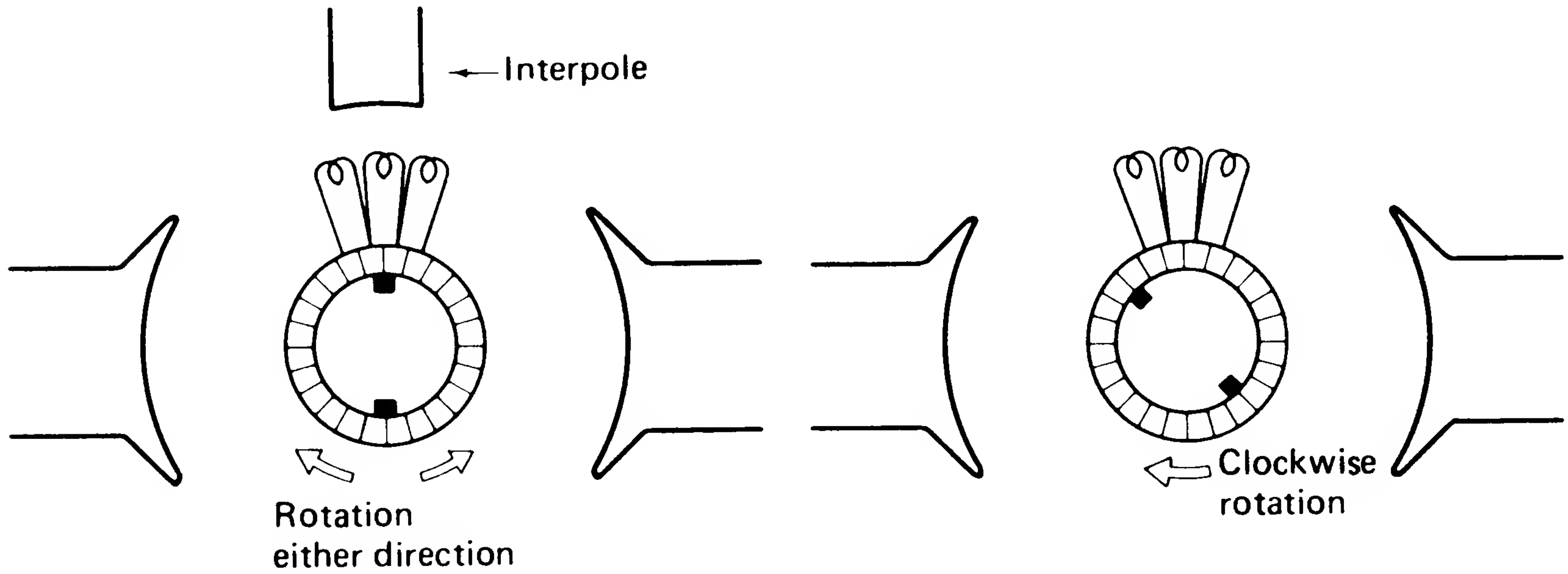


Fig. 6–68. The correct brush positions for interpole and noninterpole motors.

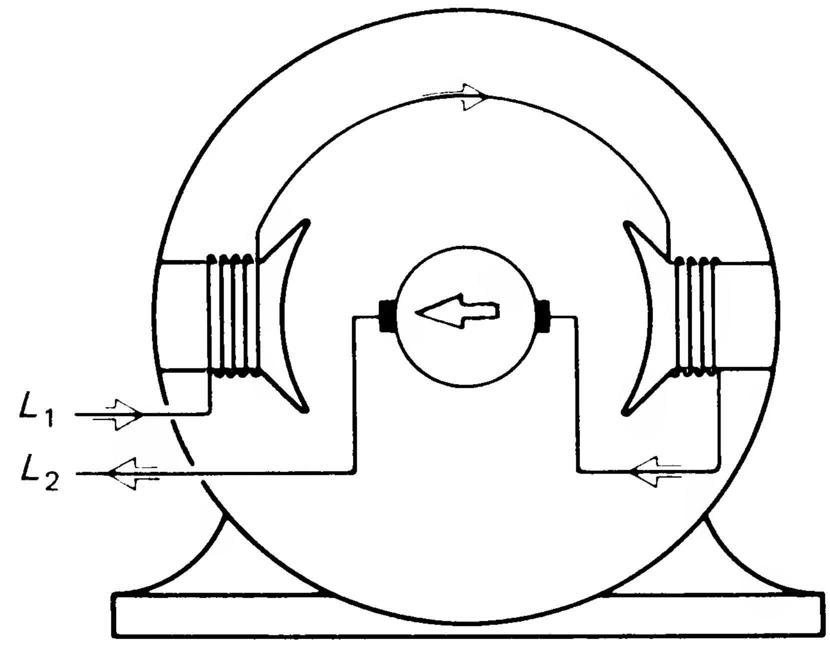


Fig. 6–69. The same amount of current flows through all elements of a series motor.

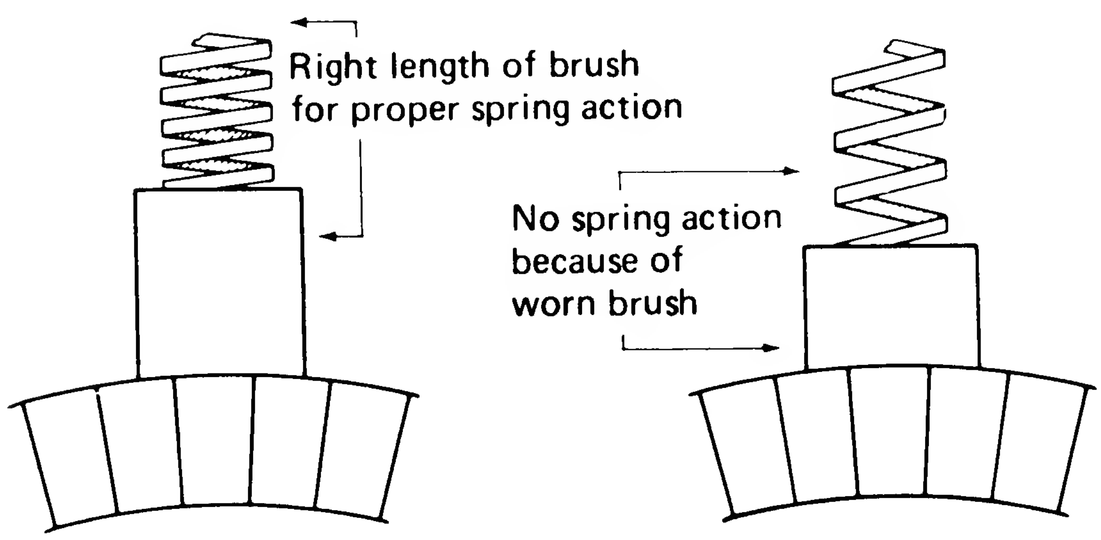


Fig. 6–70. Two diagrams showing the tension in the springs with brushes of different length.

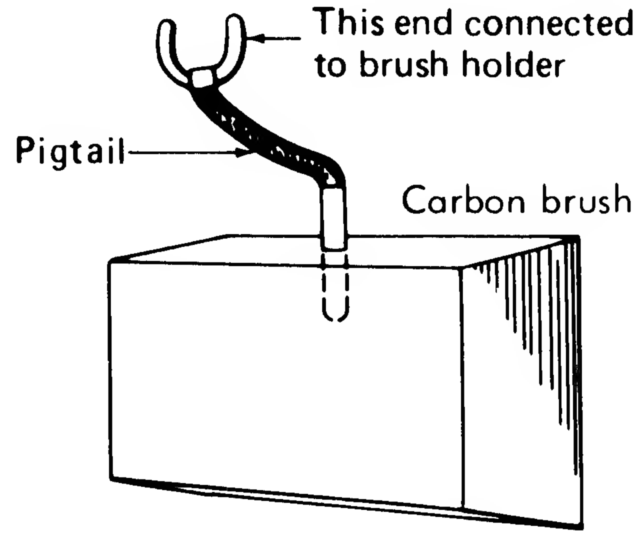


Fig. 6-71. A common type of pigtail brush.

CHAPTER 7

Direct-current Motor Control

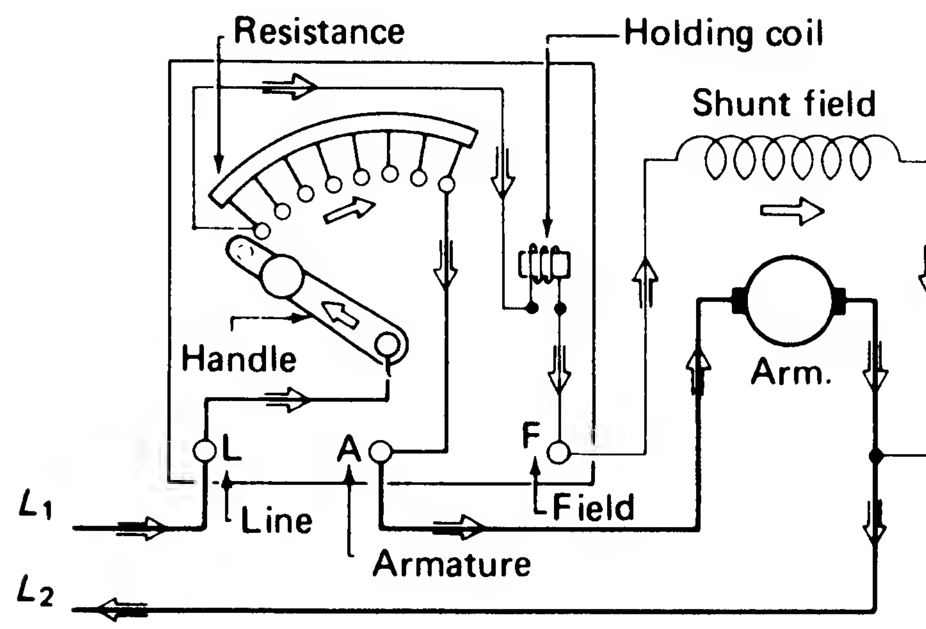


Fig. 7-1. A three-point starting box connected to a shunt motor.

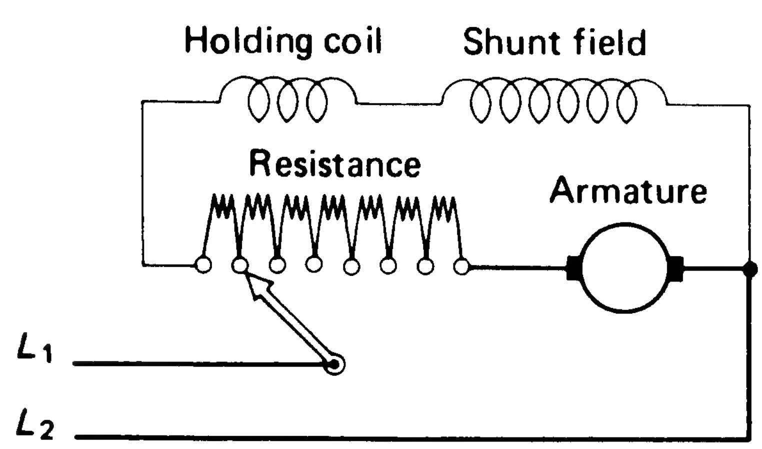


Fig. 7-2. A simplified diagram of **Fig. 7-1.**

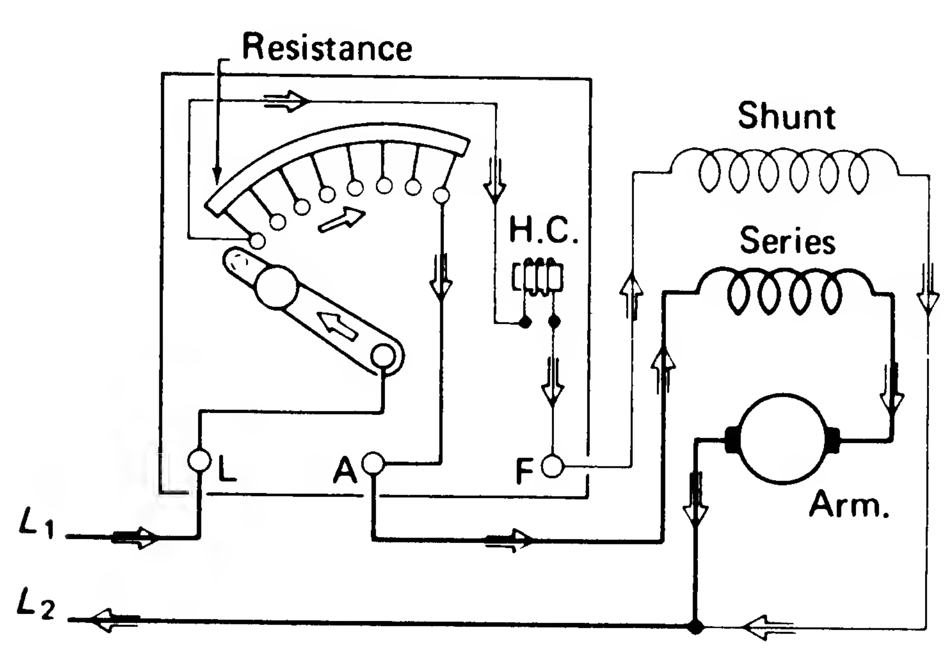
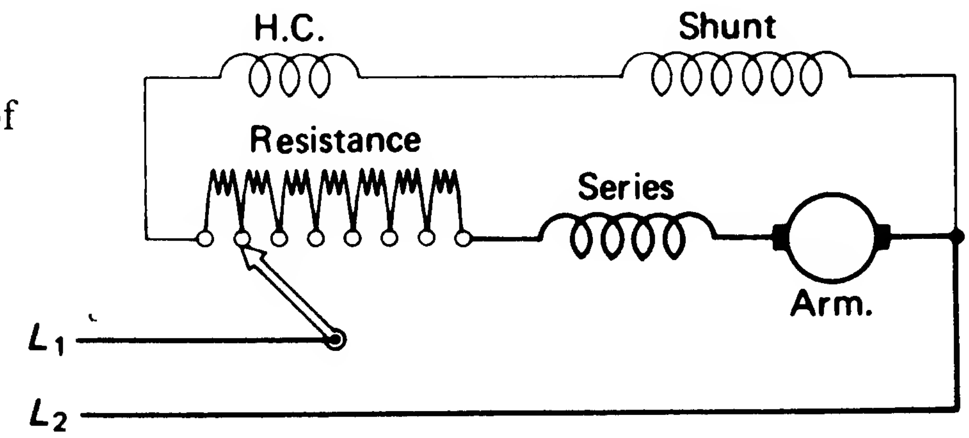


Fig. 7-3. A three-point starting box connected to a compound motor.

Fig. 7-4. A simplified diagram of **Fig. 7-3.**



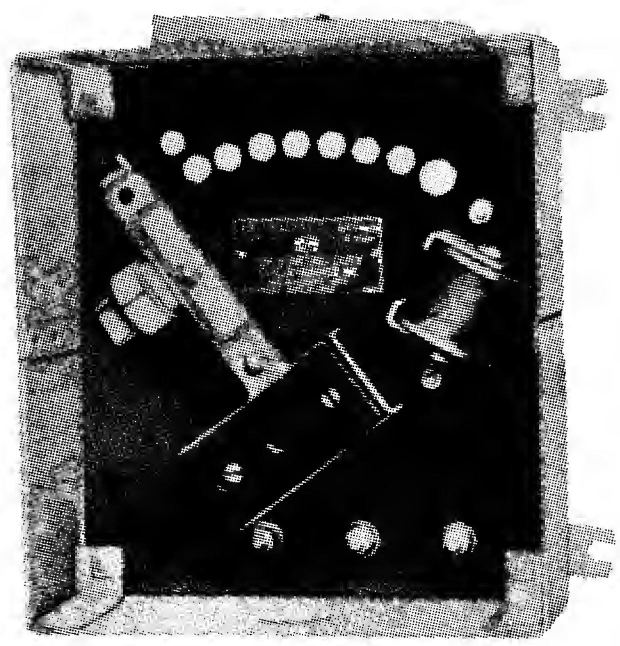


Fig. 7-5. A reduced voltage manual nonreversing starter. *(Cutler Hammer)*

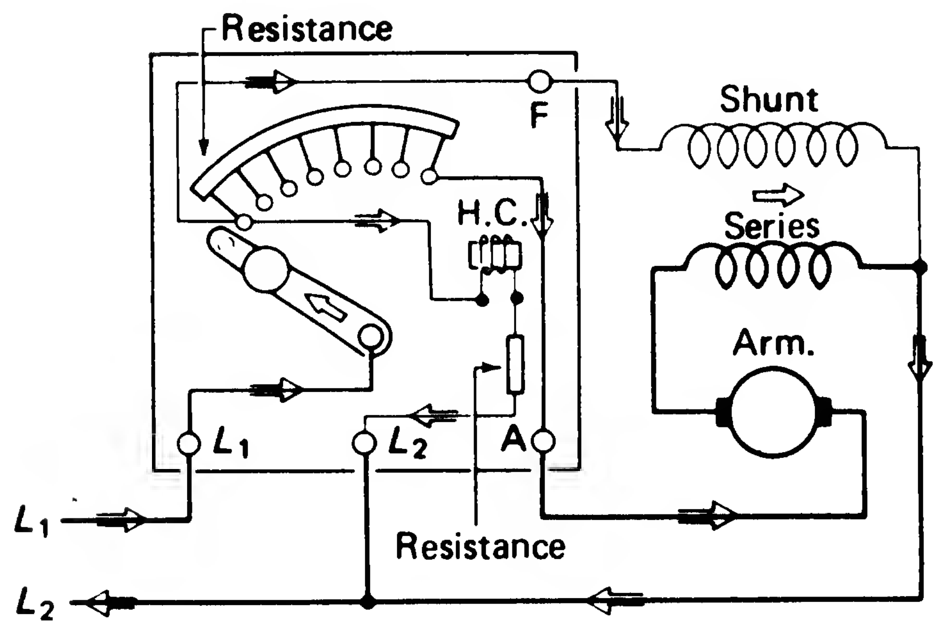


Fig. 7-6. A four-point starting box connected to a compound motor.

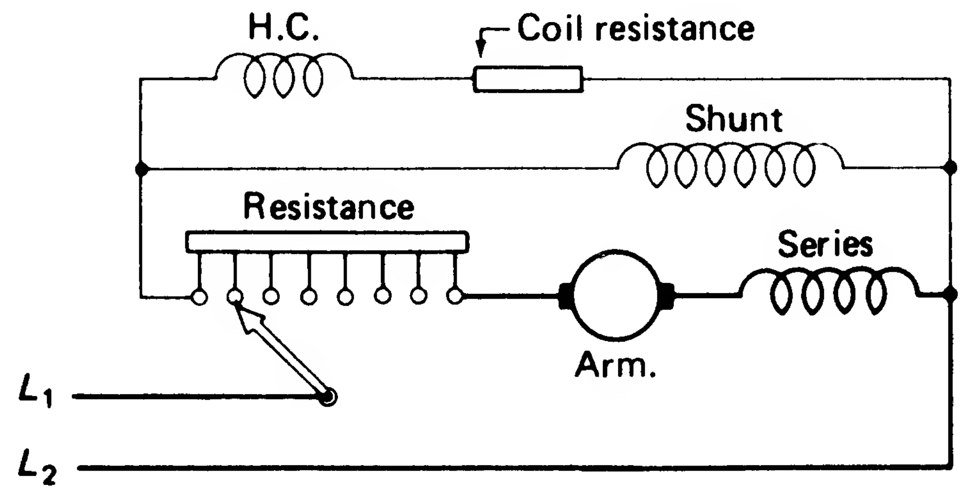


Fig. 7–7. A schematic diagram of the current paths for a four-point box connected to a compound motor.

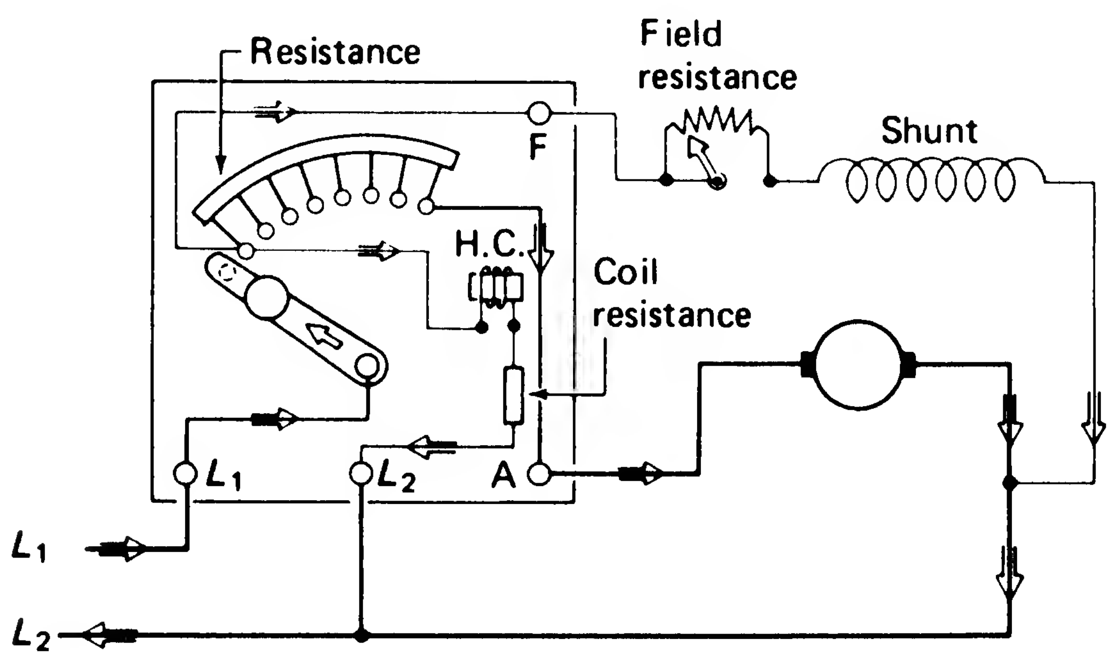


Fig. 7–8. A four-point box with a variable field resistance added for speed control.

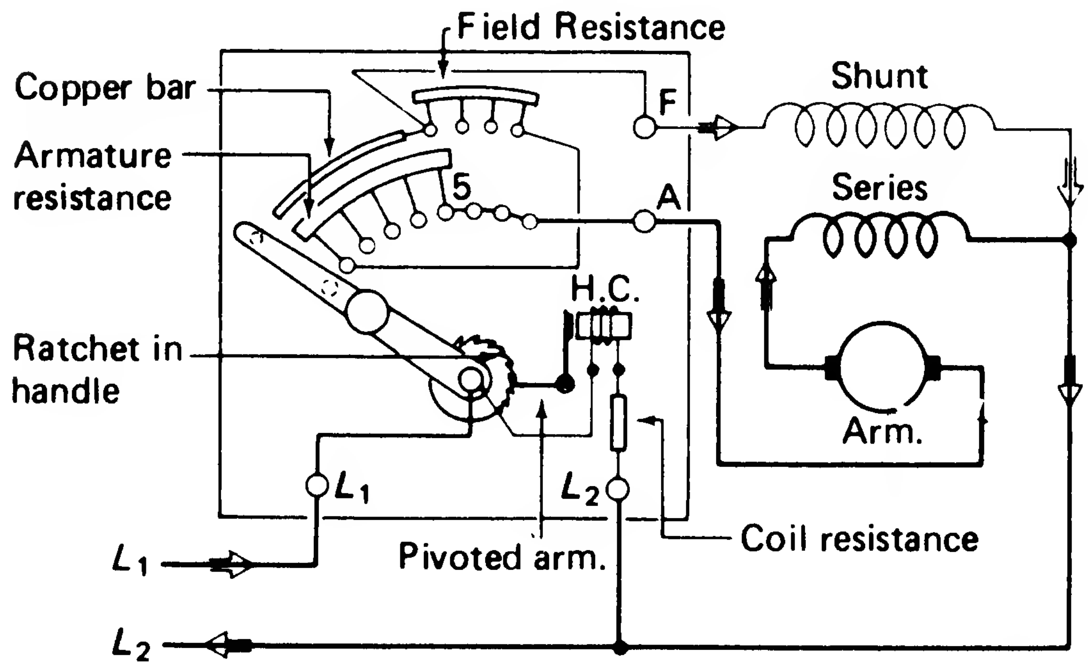


Fig. 7–9. A four-point speed-regulating rheostat connected to a compound motor.

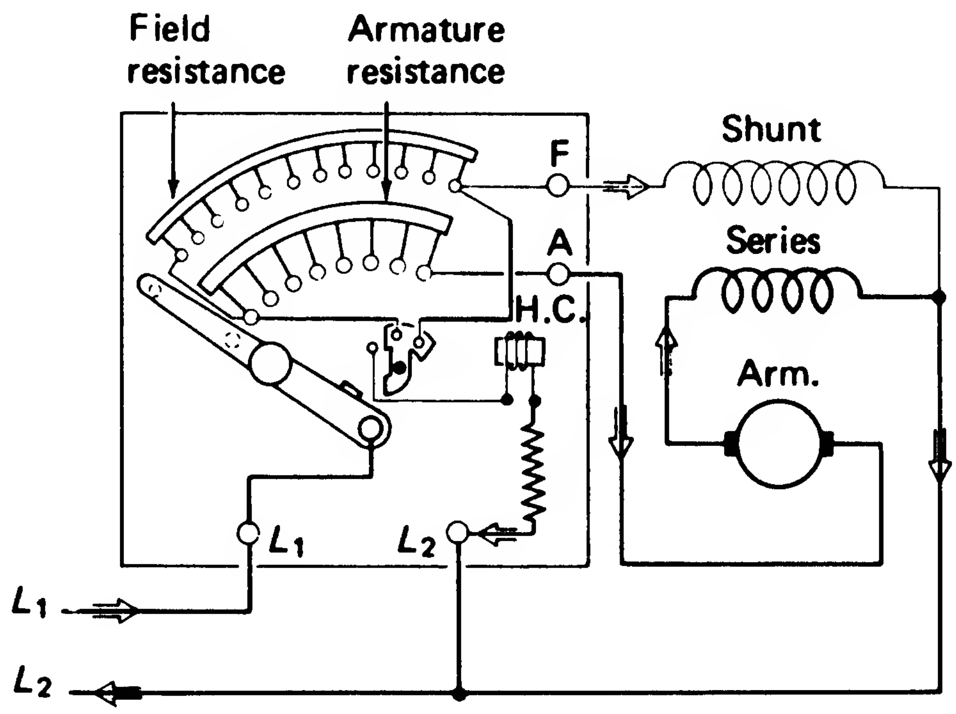


Fig. 7-10. A four-point starting box and speed-regulating rheostat connected to a compound motor.

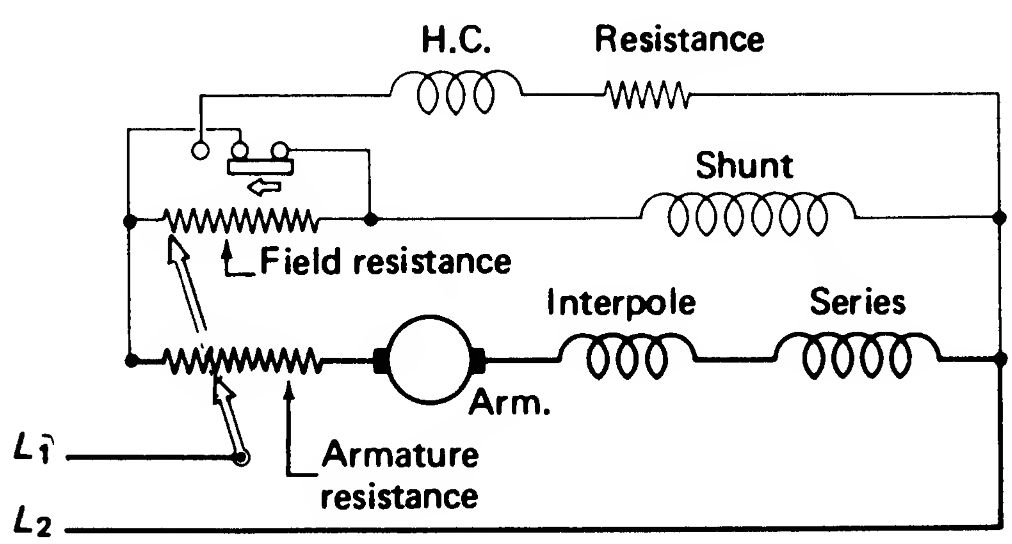


Fig. 7-11. A simplified diagram of **Fig. 7-10.**

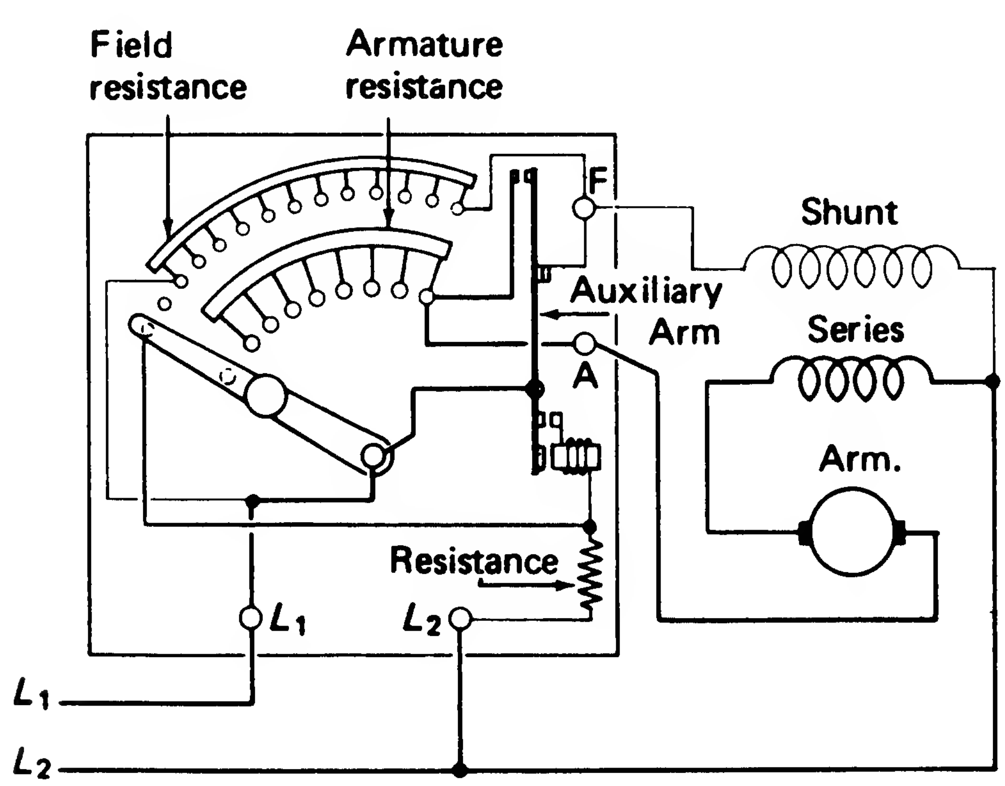
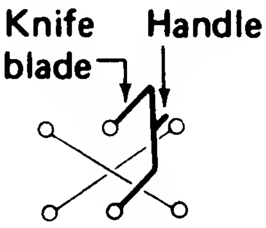


Fig. 7-12. A combination starter and speed regulator.

Fig. 7-13. A double-pole, double-throw knife switch.



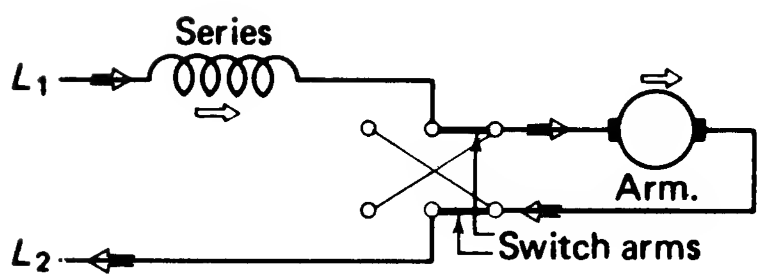
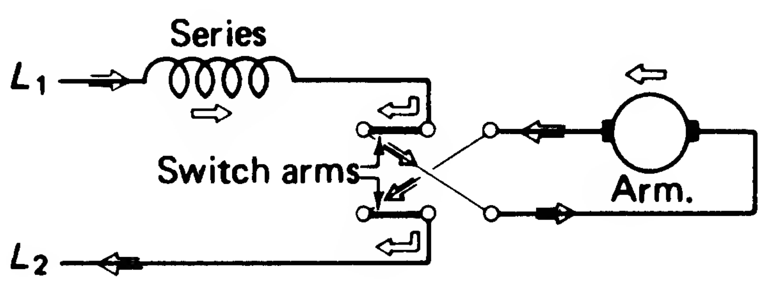


Fig. 7-14. A double-pole, double-throw switch connected to reverse the armature current of a series motor. Note the direction of current in the armature with the switch thrown to the right.

Fig. 7-15. A circuit of Fig. 7-14 with the switch thrown in the opposite direction.



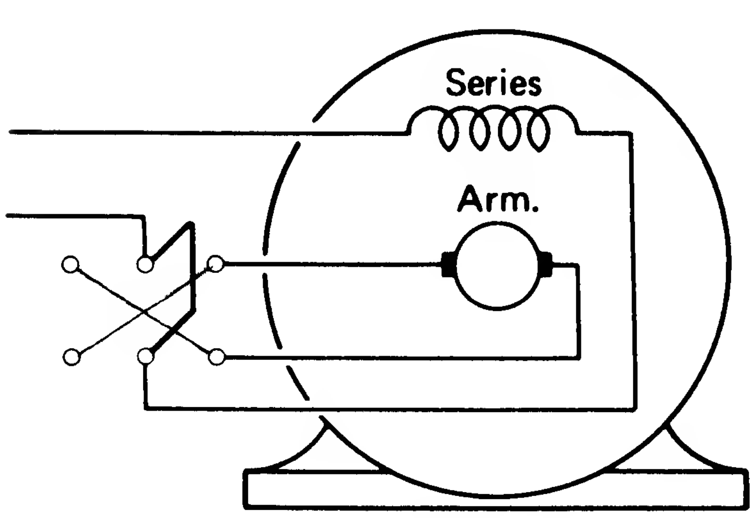


Fig. 7-16. A series motor connected to a double-pole, double-throw switch for reversing.

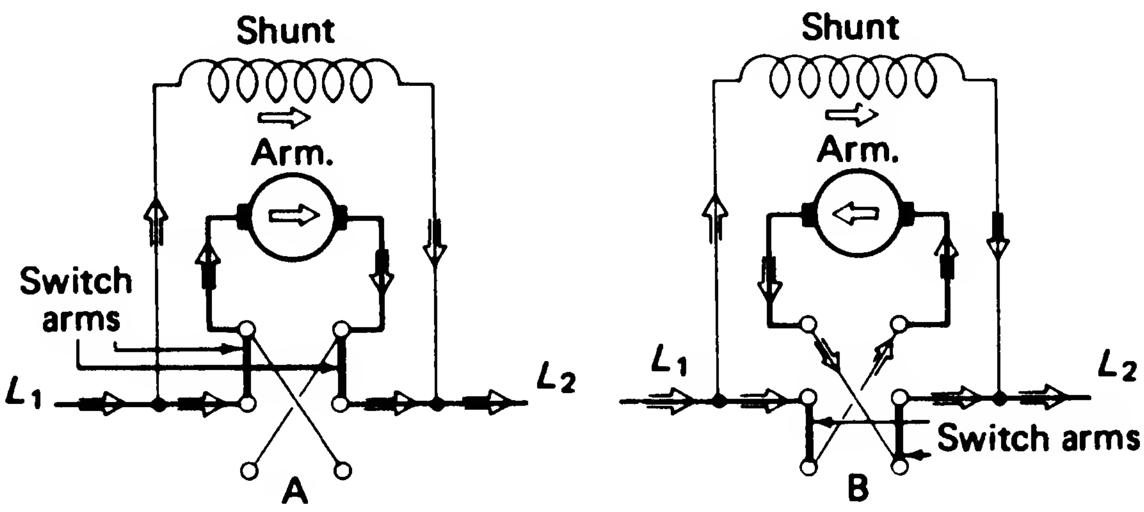


Fig. 7-17. At (a) with the switch thrown up, the armature current of a shunt motor is flowing to the right. At (b) with the switch thrown down, the armature current is flowing to the left.

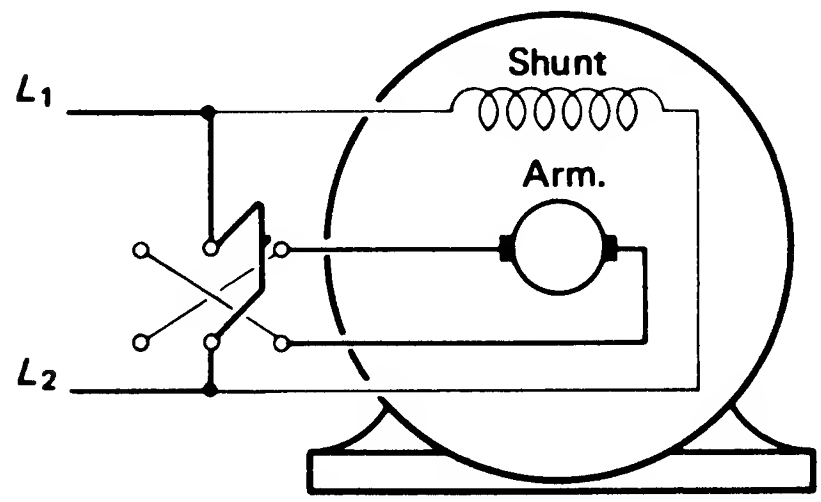


Fig. 7-18. A shunt motor connected to a double-pole, double-throw switch.

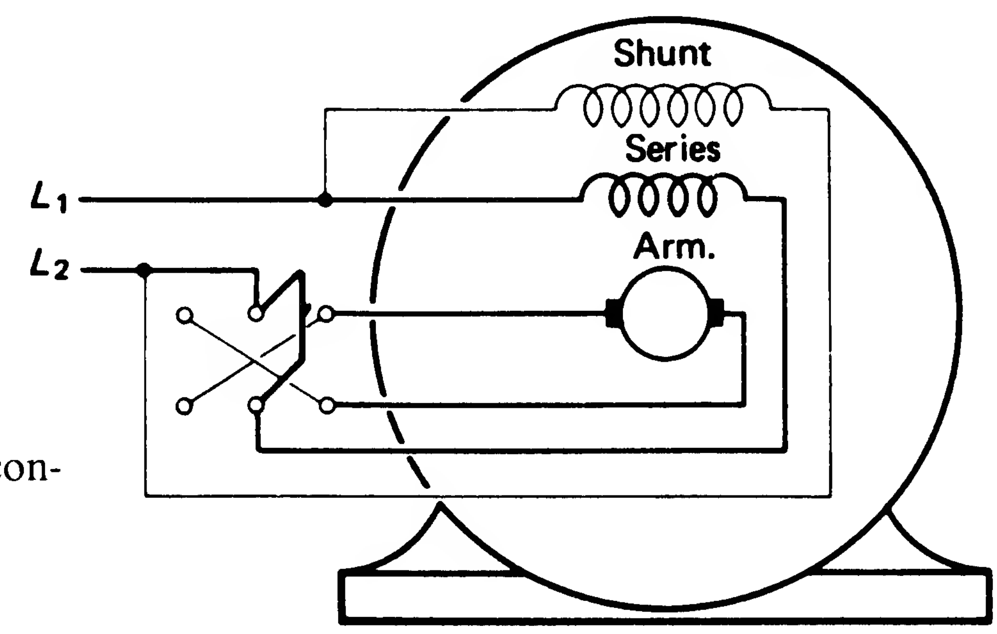


Fig. 7-19. A compound motor connected to a reversing switch.

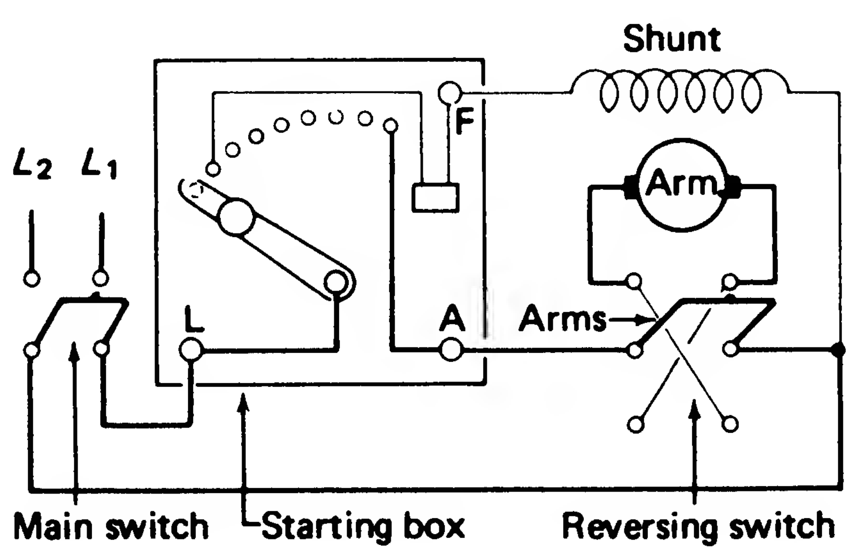


Fig. 7-20. A shunt motor connected to three-point box and reversing switch.

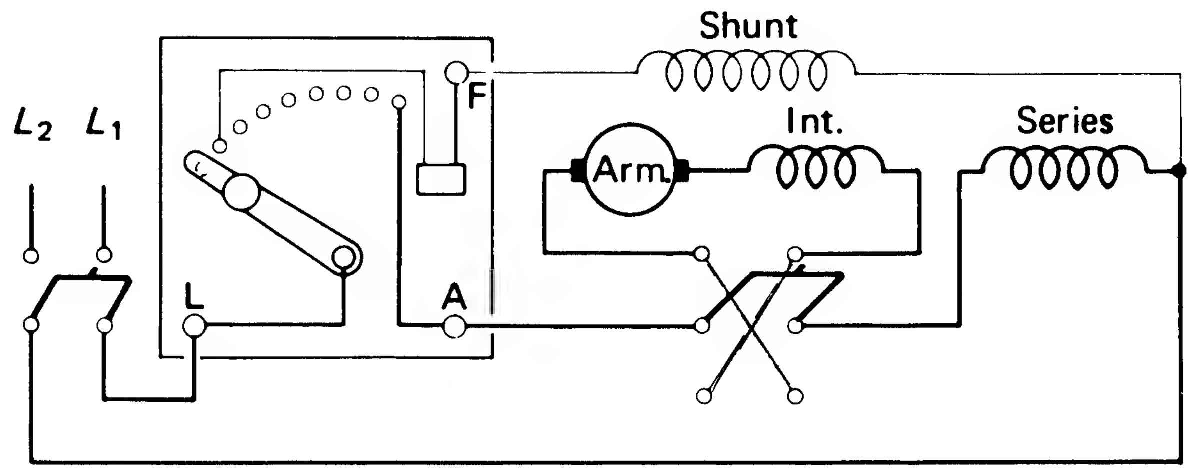


Fig. 7–21. A compound motor connected to three-point box and reversing switch. Note that the armature and interpole are reversed as a unit.

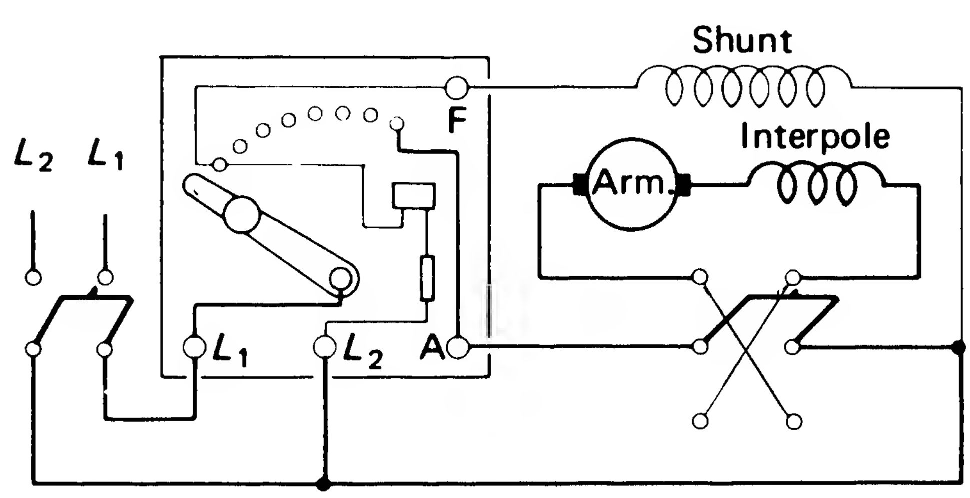


Fig. 7–22. A shunt motor connected to a four-point box and reversing switch.

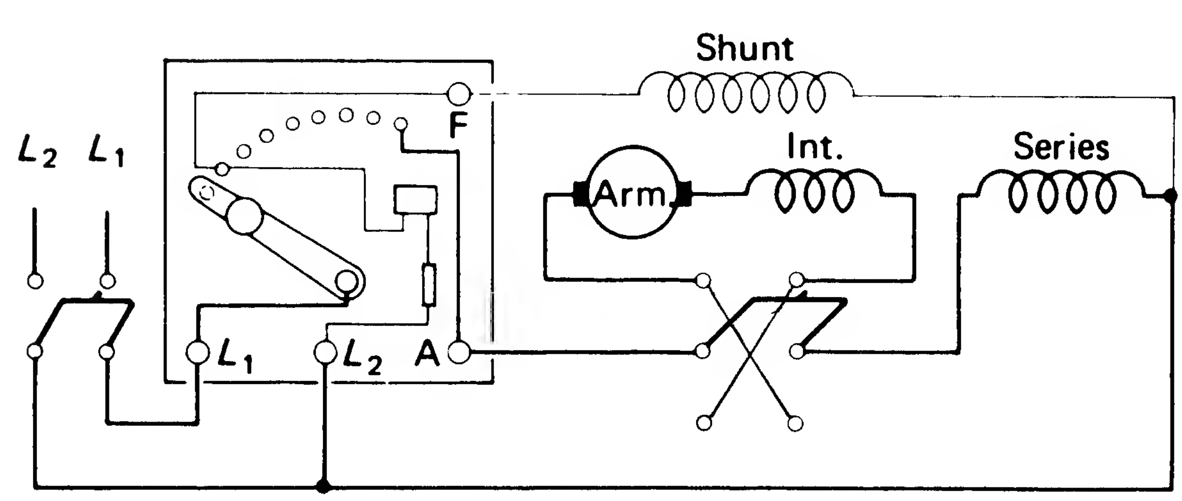


Fig. 7–23. A compound motor connected to a four-point box and reversing switch.

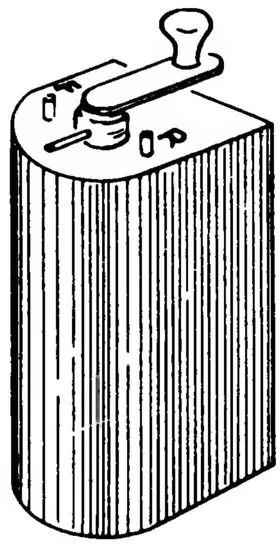


Fig. 7-24. General appearance of a small drum switch.

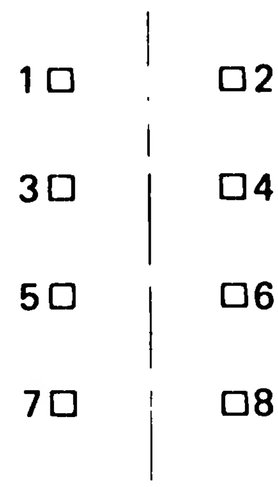


Fig. 7-25. Stationary contacts of a drum switch.

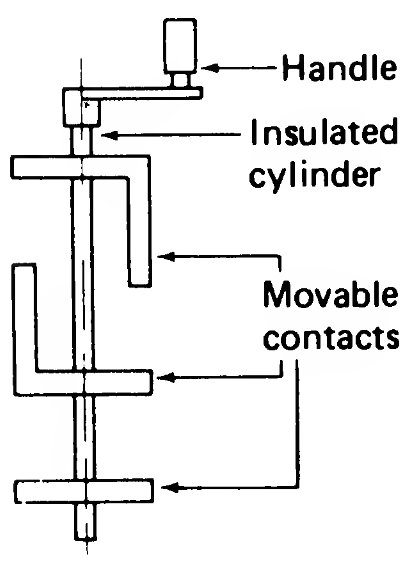


Fig. 7-26. Movable contacts of a drum switch.

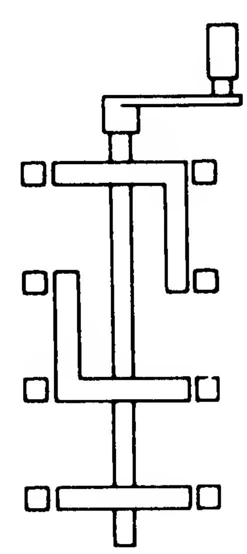


Fig. 7-27. The position of the contacts for forward rotation.

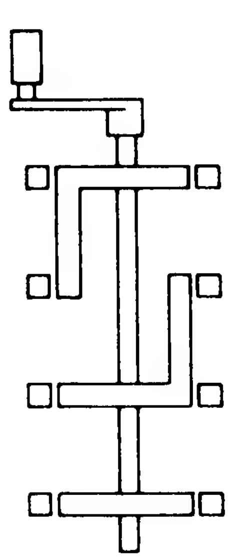


Fig. 7-28. The position of the contacts for reverse direction.

Figures 7-24; 7-25; 7-26; 7-27; 7-28

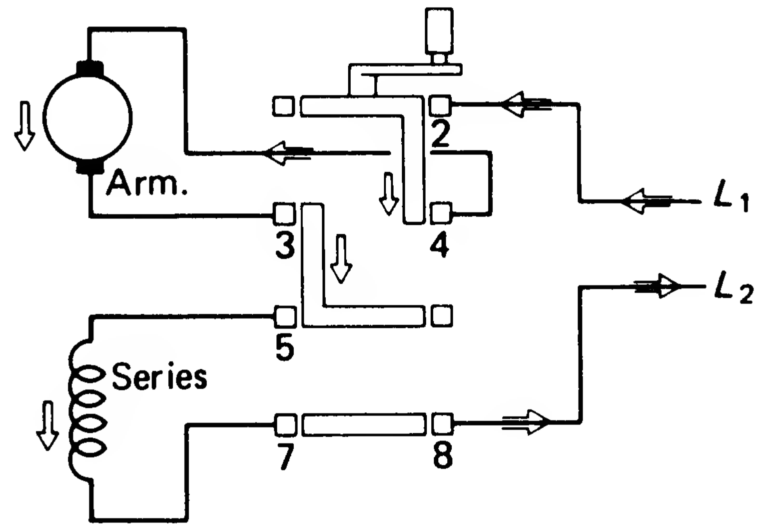


Fig. 7-29. A series motor connected to a drum switch for clockwise direction.

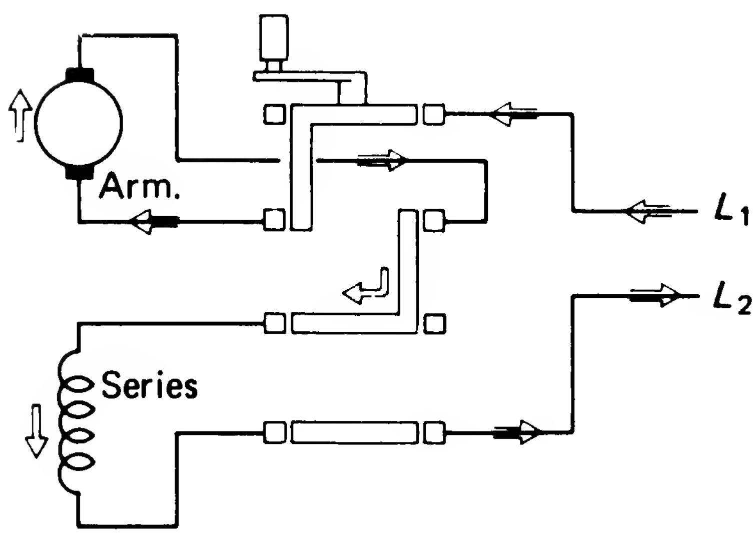


Fig. 7-30. A drum switch connection for counterclockwise rotation of a series motor.

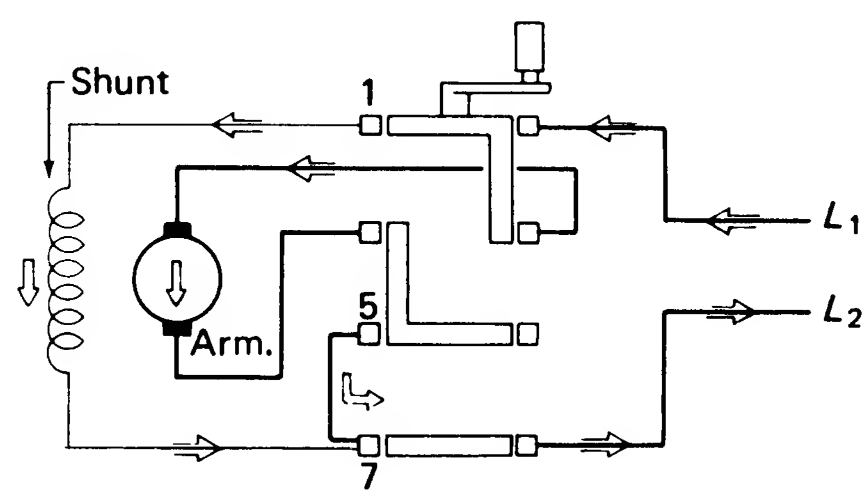


Fig. 7-31. A shunt motor connected to a drum switch.

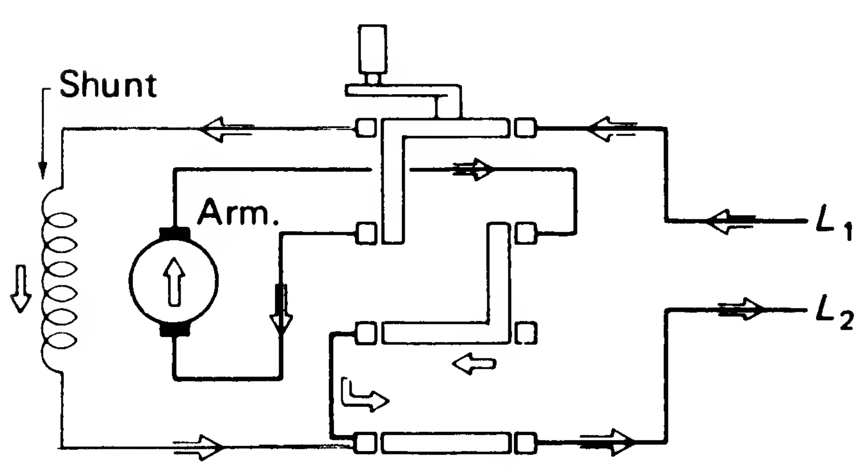


Fig. 7-32. A shunt motor of **Fig. 7-31** reversed by drum switch.

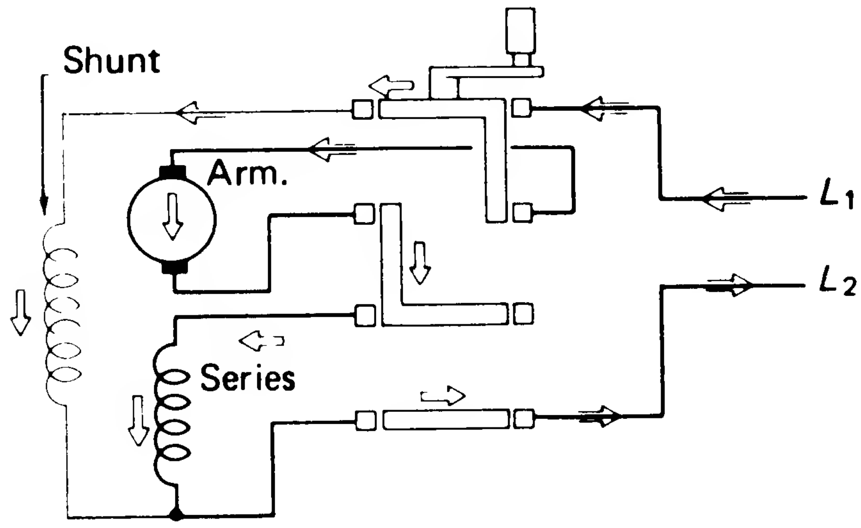


Fig. 7-33a. A compound motor connected to a drum switch for clockwise direction.

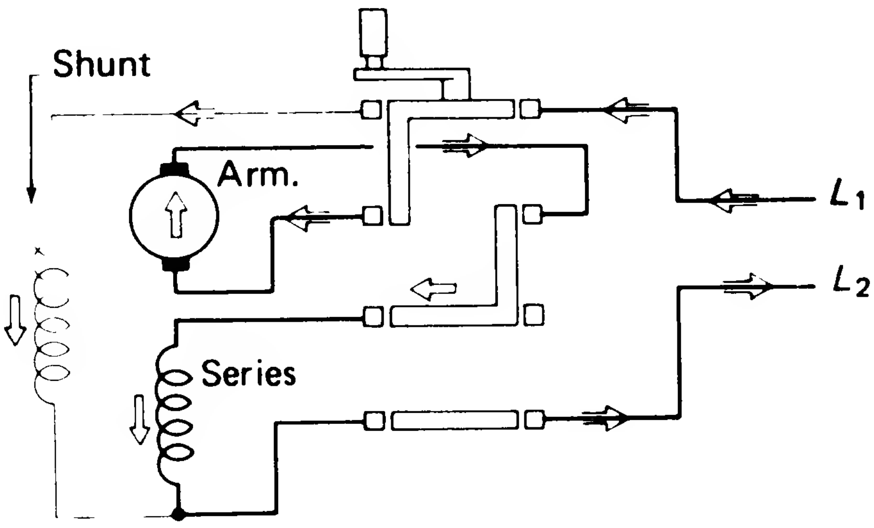


Fig. 7-33b. A compound motor connected for counterclockwise direction.

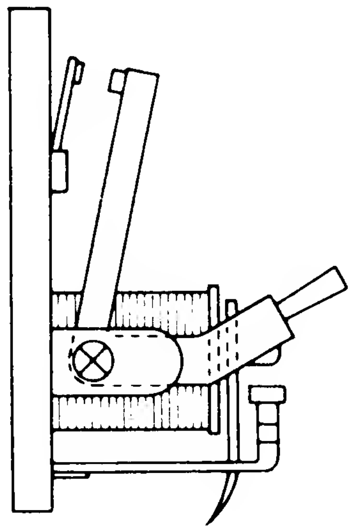


Fig. 7-34. A magnetic circuit breaker.

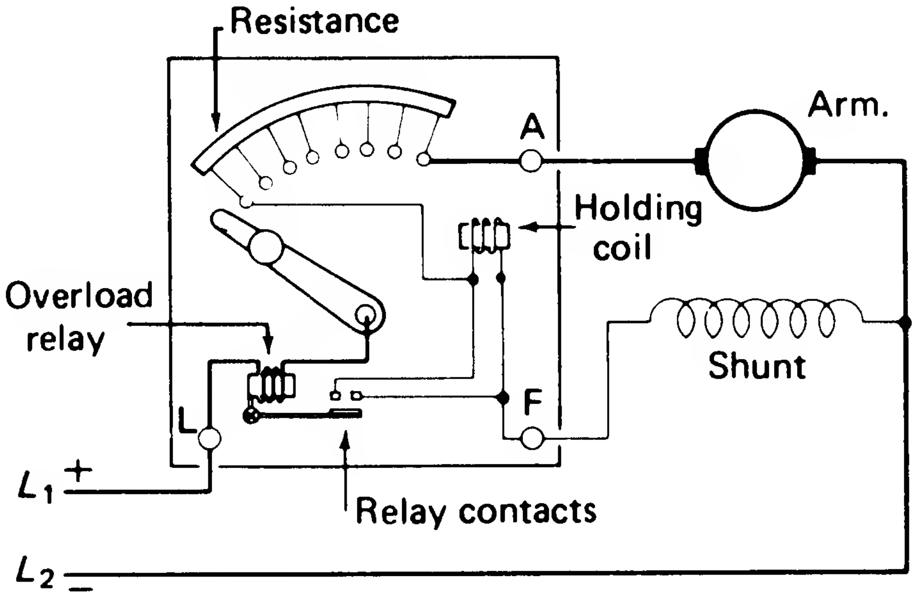


Fig. 7-35. An overload relay connected in a three-point starting box.

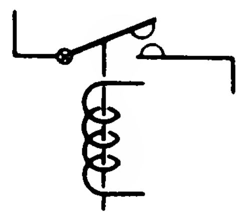
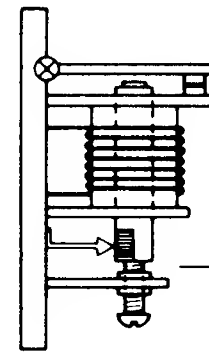


Fig. 7-36. An overload relay with a plunger to open the contacts.



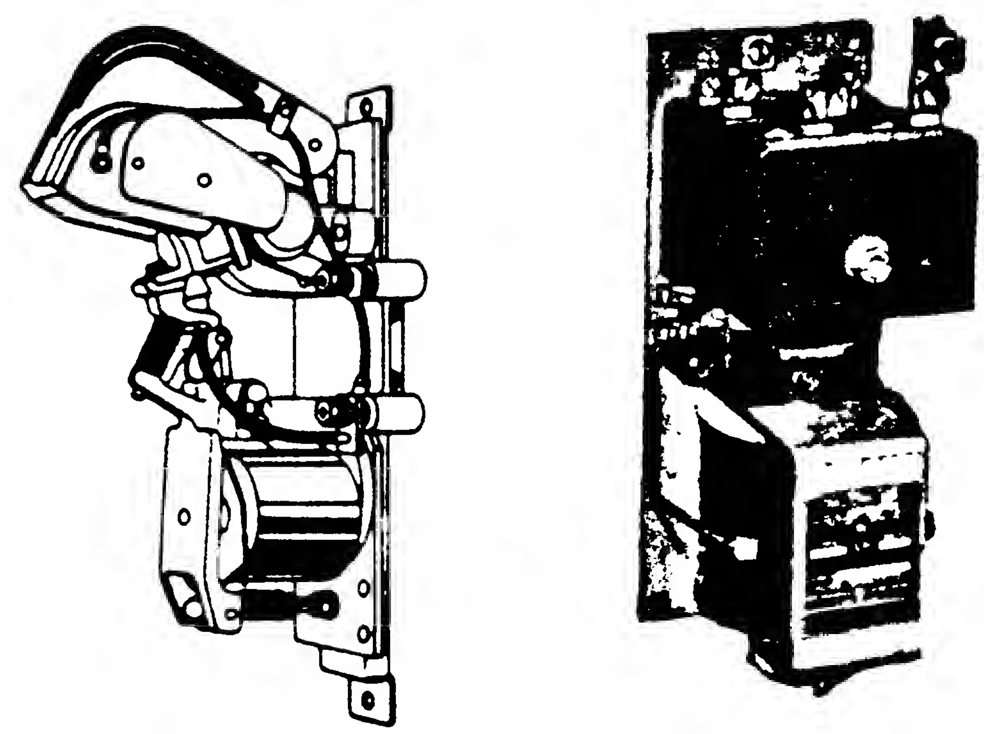


Fig. 7-37. A dc magnetic contactor.

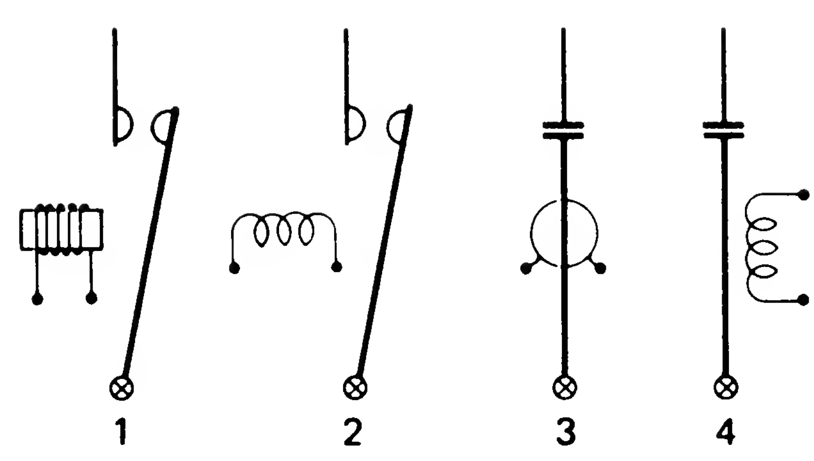


Fig. 7-38. Methods of denoting a magnetic contactor.

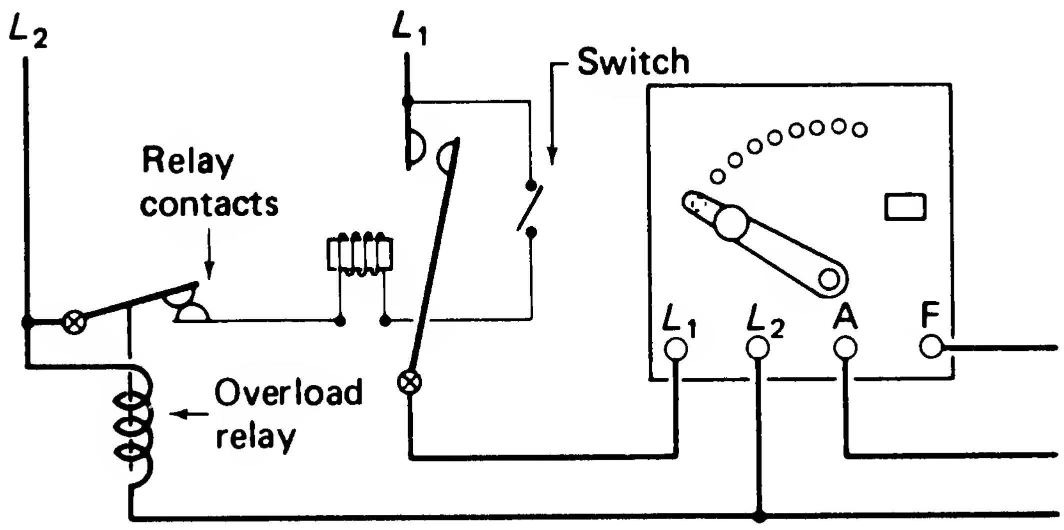


Fig. 7-39. A magnetic overload relay used in conjunction with a magnetic contactor.

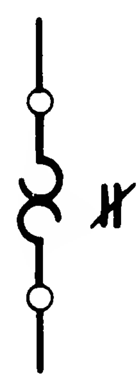


Fig. 7-40. Methods of denoting a thermal relay. The figures to the right indicate contacts.

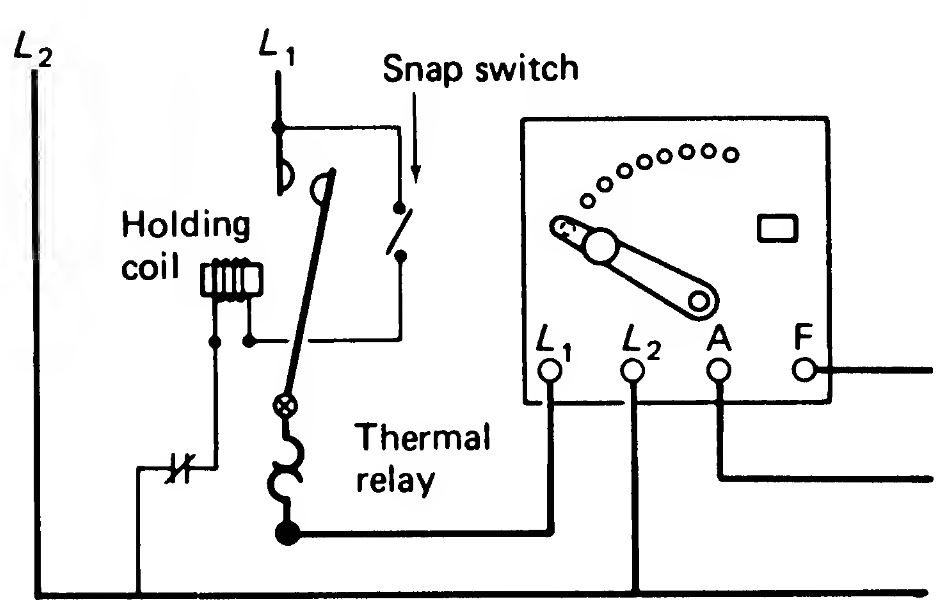


Fig. 7-41. A thermal overload relay used with a magnetic contactor.

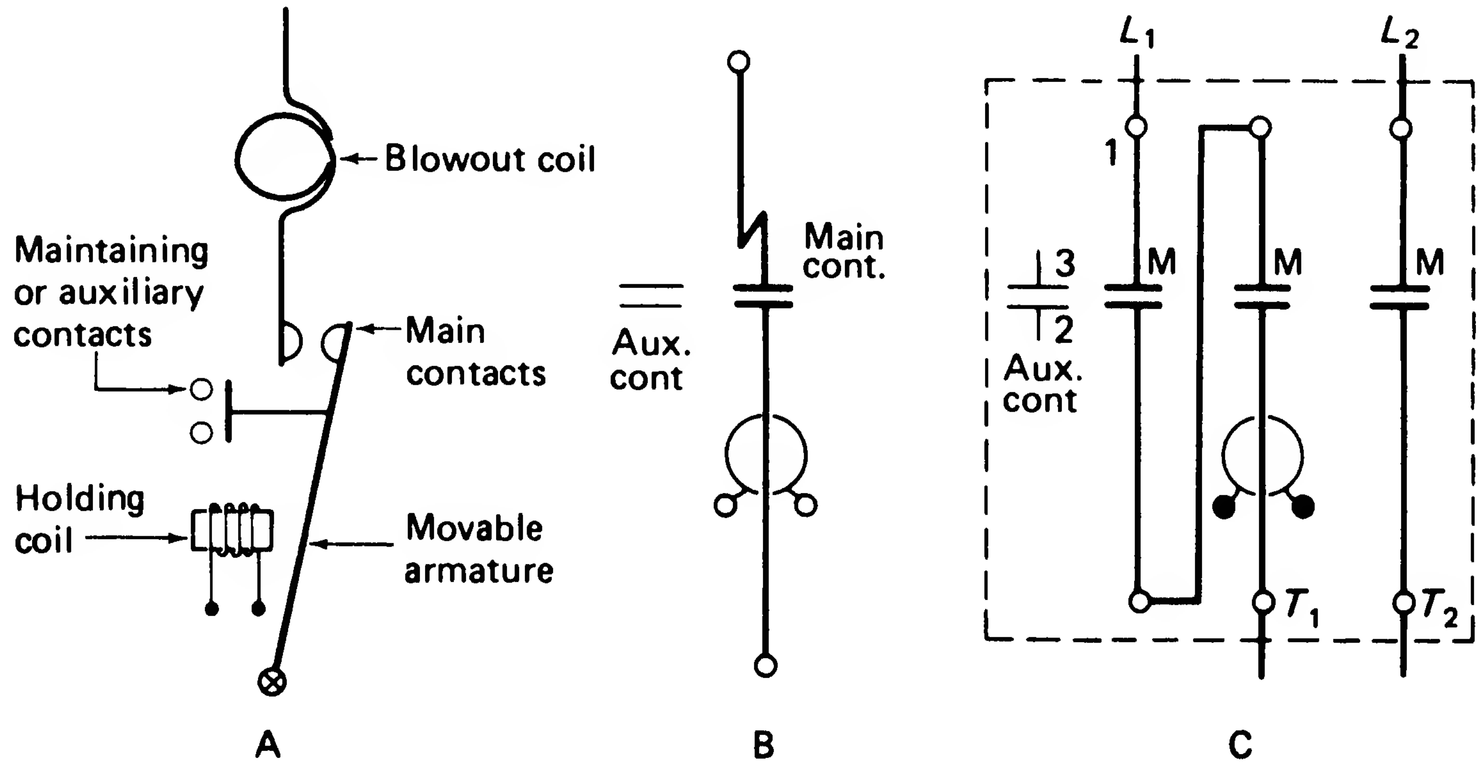


Fig. 7-42 a. The parts of a magnetic switch. b. Method of denoting a magnetic switch. c. Two-pole contactor.

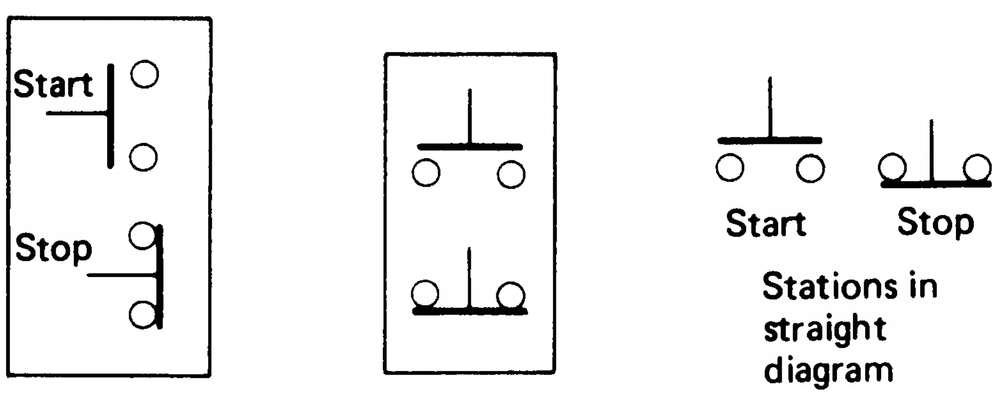


Fig. 7-43. Methods of showing four-contact, START-STOP, pushbutton stations.

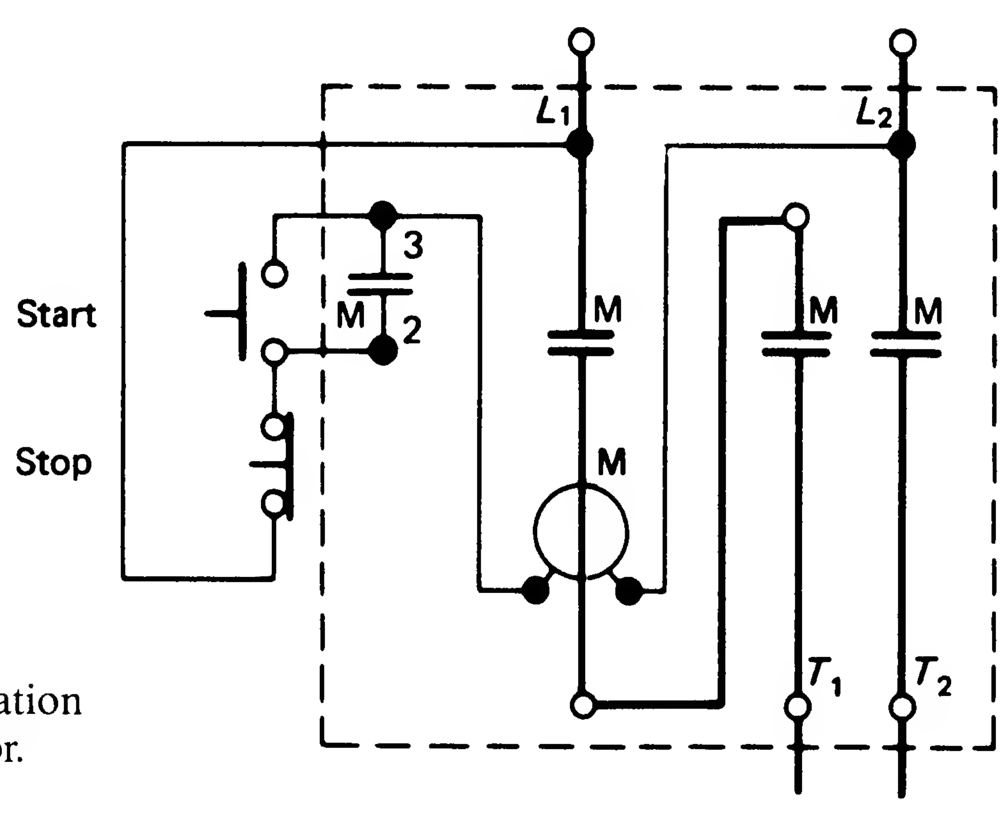


Fig. 7-44. A START-STOP station connected to a magnetic contactor.

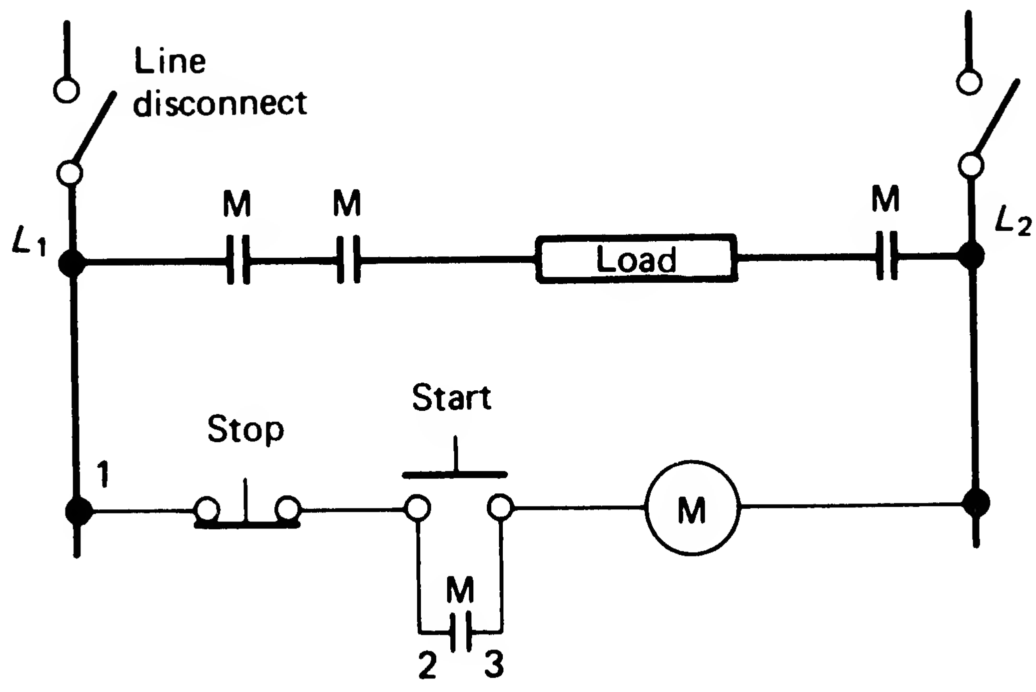


Fig. 7-45. A START-STOP station connected to a magnetic switch.

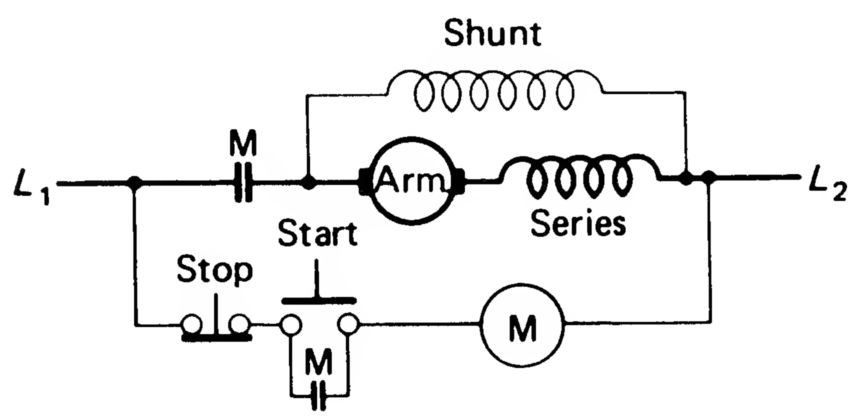


Fig. 7-46. An elementary diagram of a compound motor, START-STOP station and contactor.

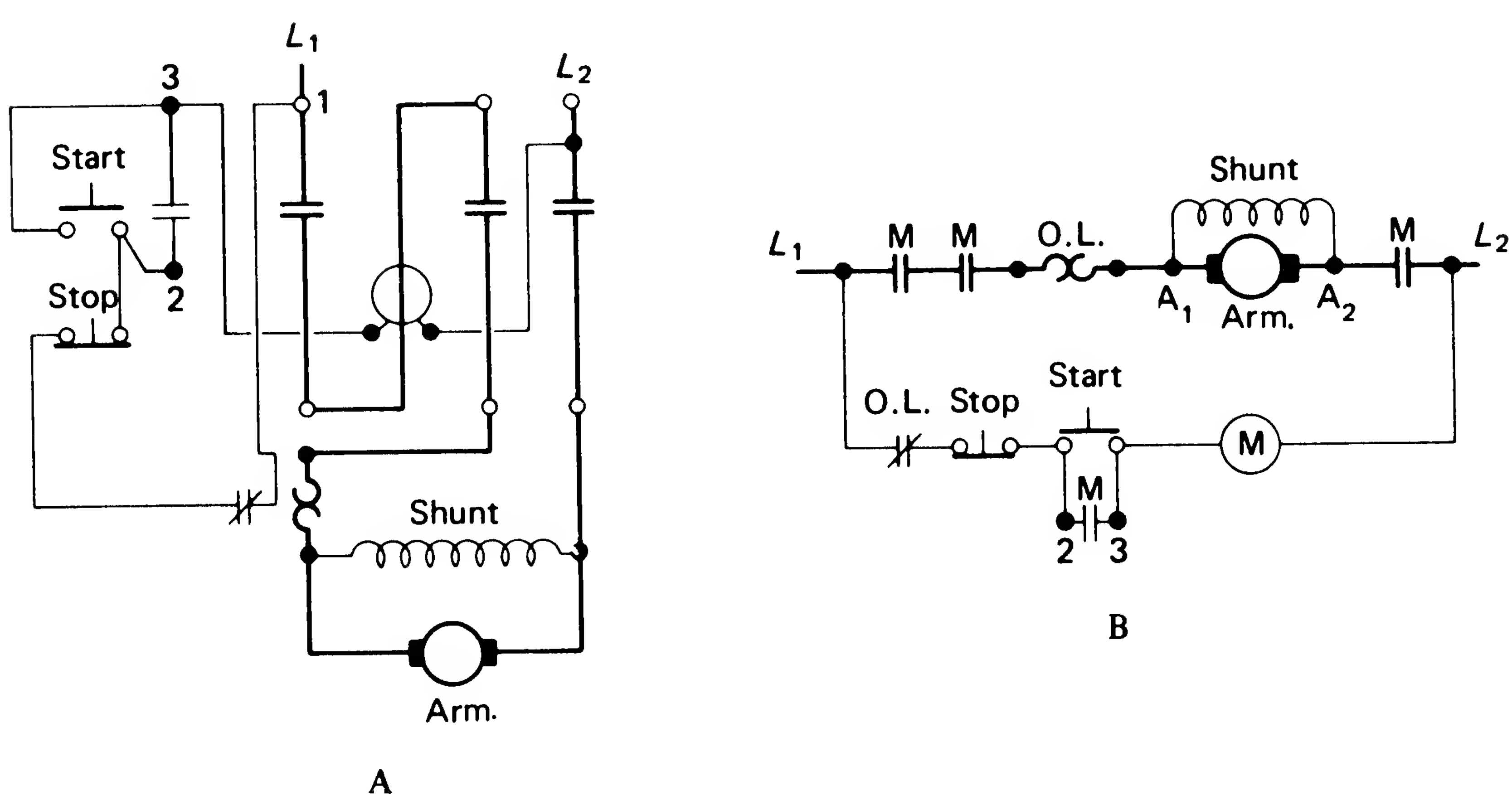


Fig. 7-47. Wiring diagram of a two-pole full-voltage starter connected to a dc motor.

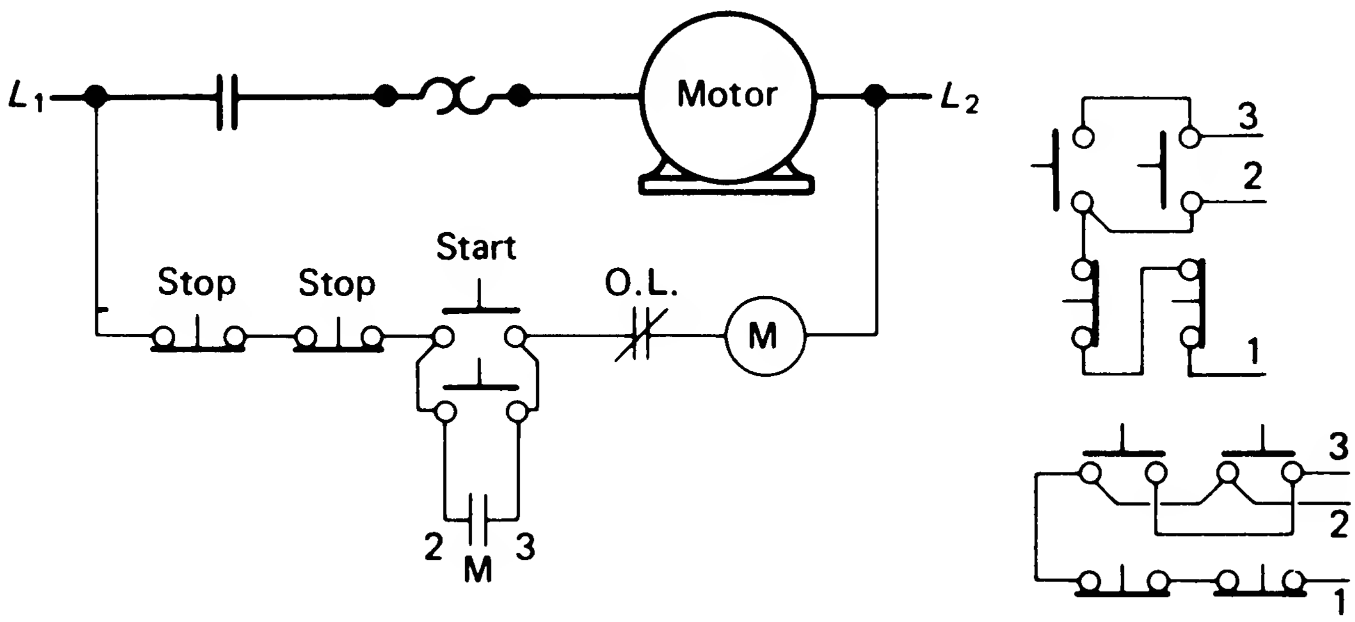


Fig. 7-48. Two START-STOP stations controlling a dc starter.

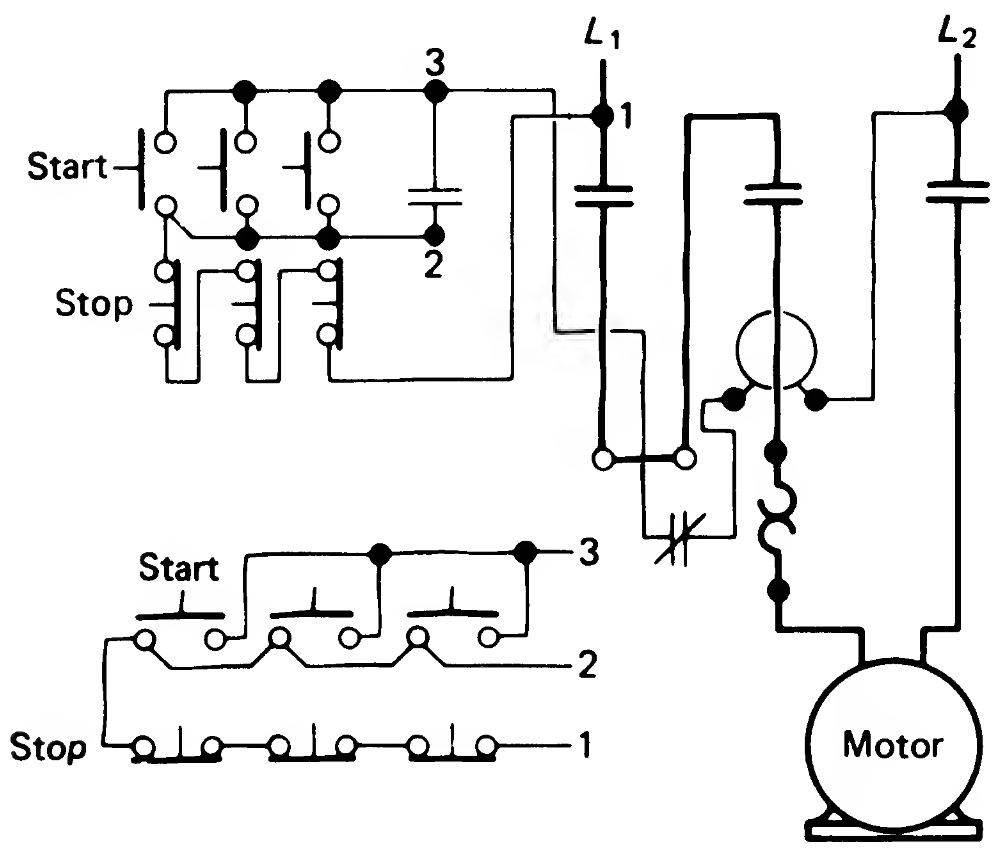


Fig. 7-49. Three START-STOP stations connected to a dc starter.

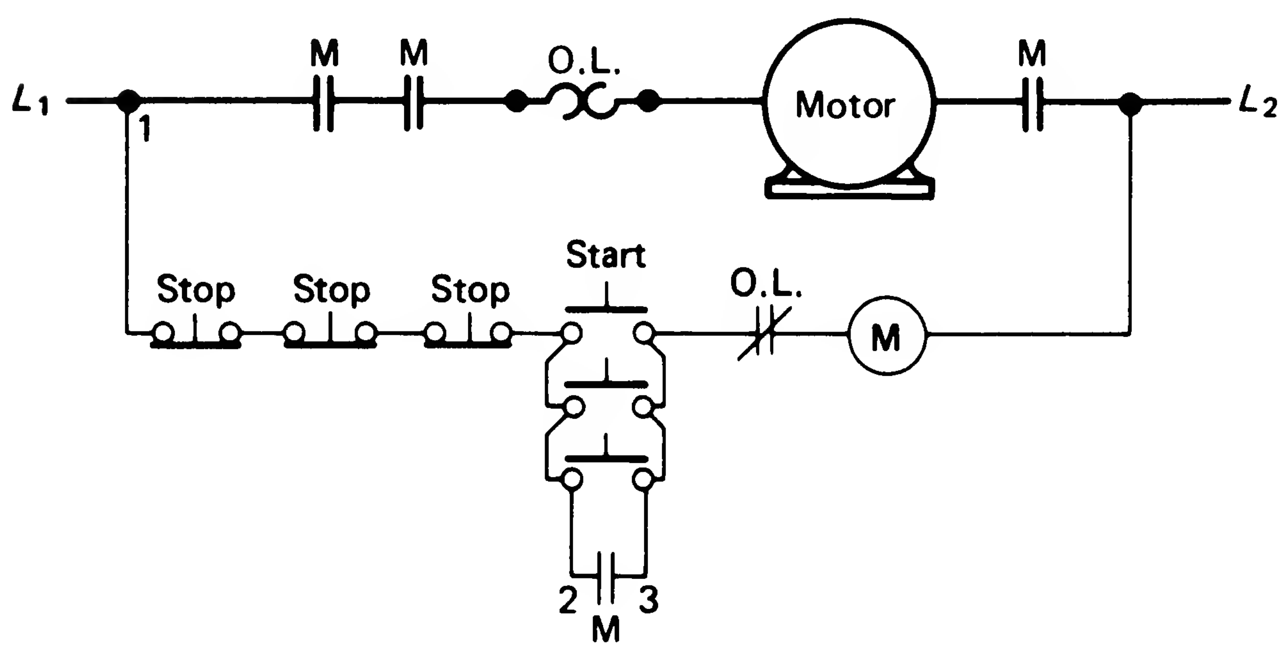


Fig. 7-50. Elementary diagram of three START-STOP station connected to a dc starter.

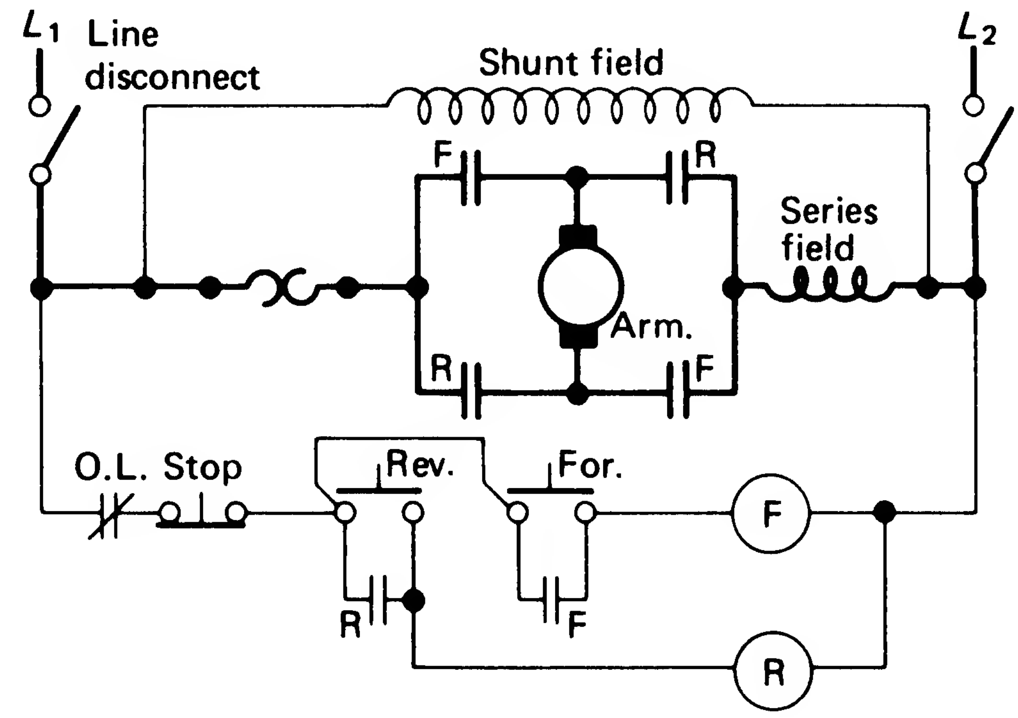


Fig. 7-51. Reversing a small compound motor, using a magnetic reversing starter and FORWARD-REVERSE-STOP station. The motor must come to a full stop before reversing.

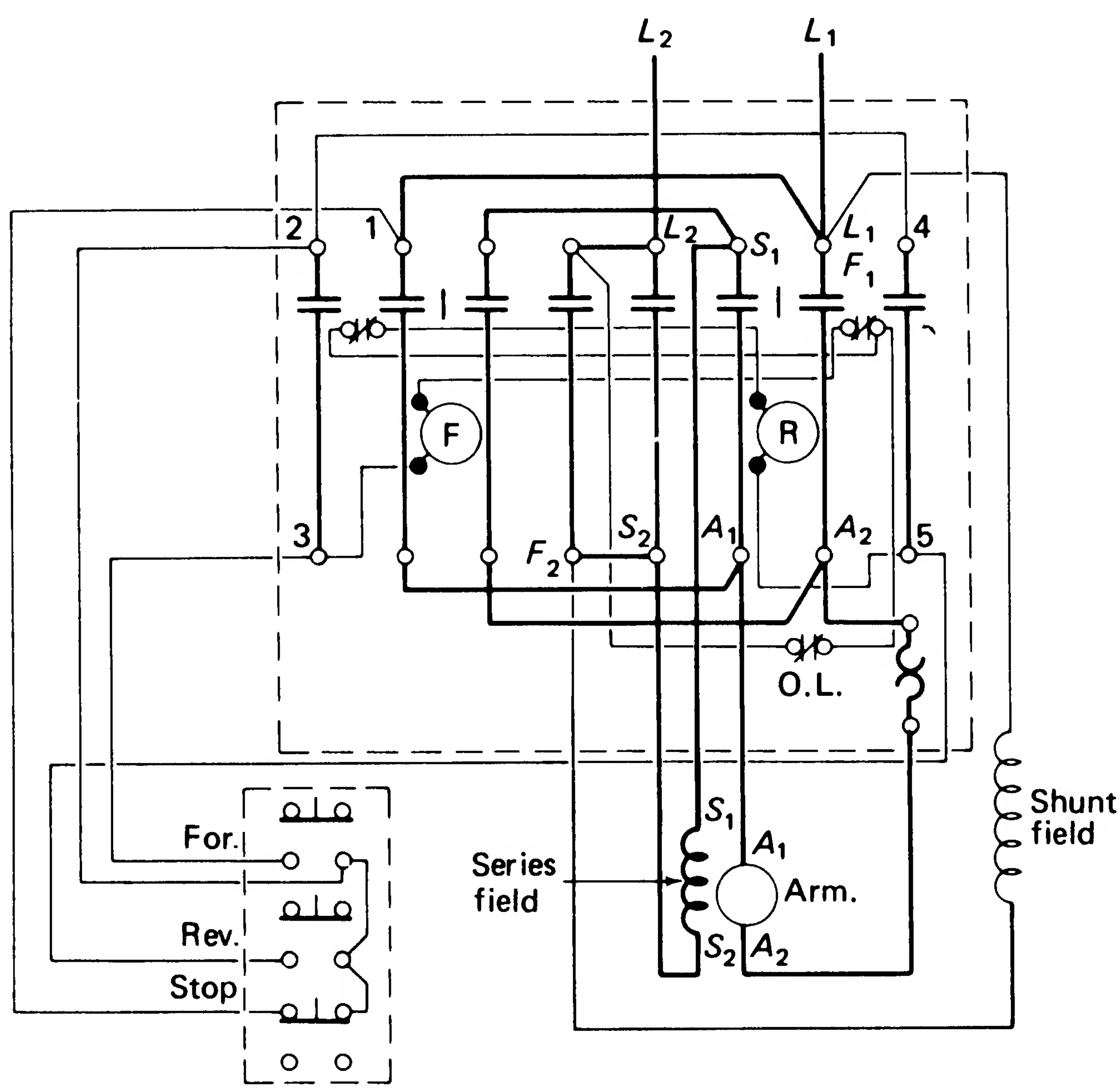


Fig. 7-52a. Wiring diagram of a reversing starter using overload protection and electrical interlocks.

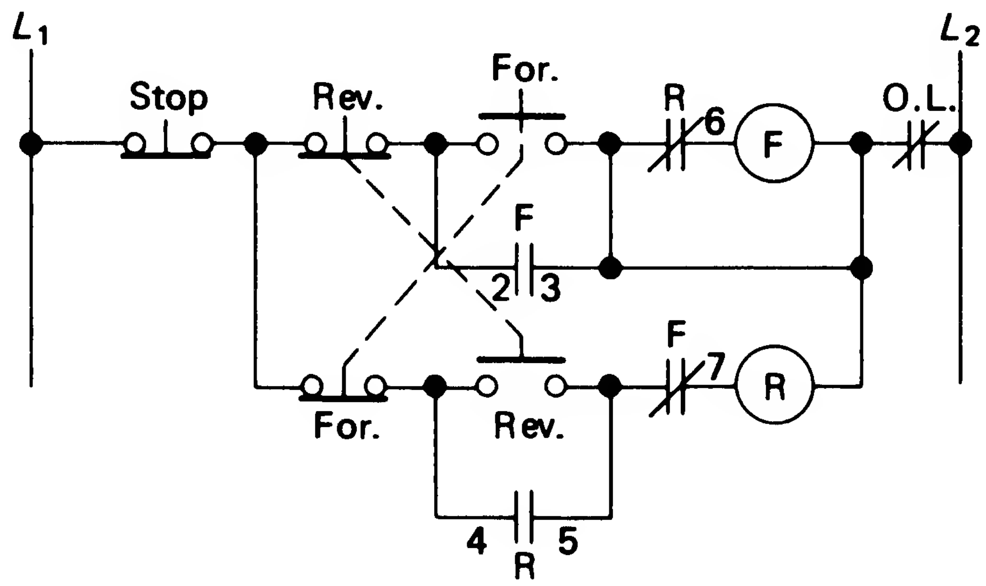


Fig. 7-52b. Control circuits for a reversing starter using front and rear contacts of the FORWARD and REVERSE buttons.

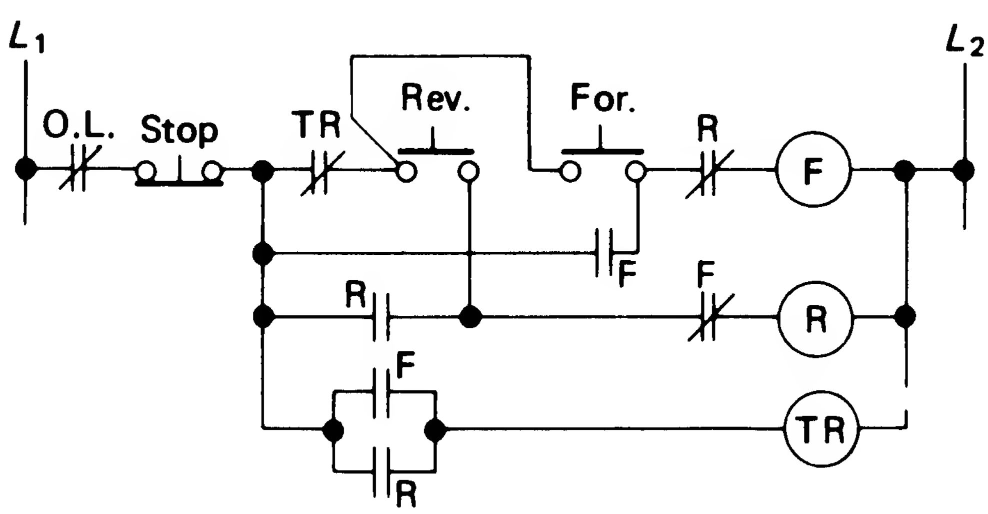


Fig. 7-53. Control circuit using timing relay to prevent reversing until motor comes to a full stop.

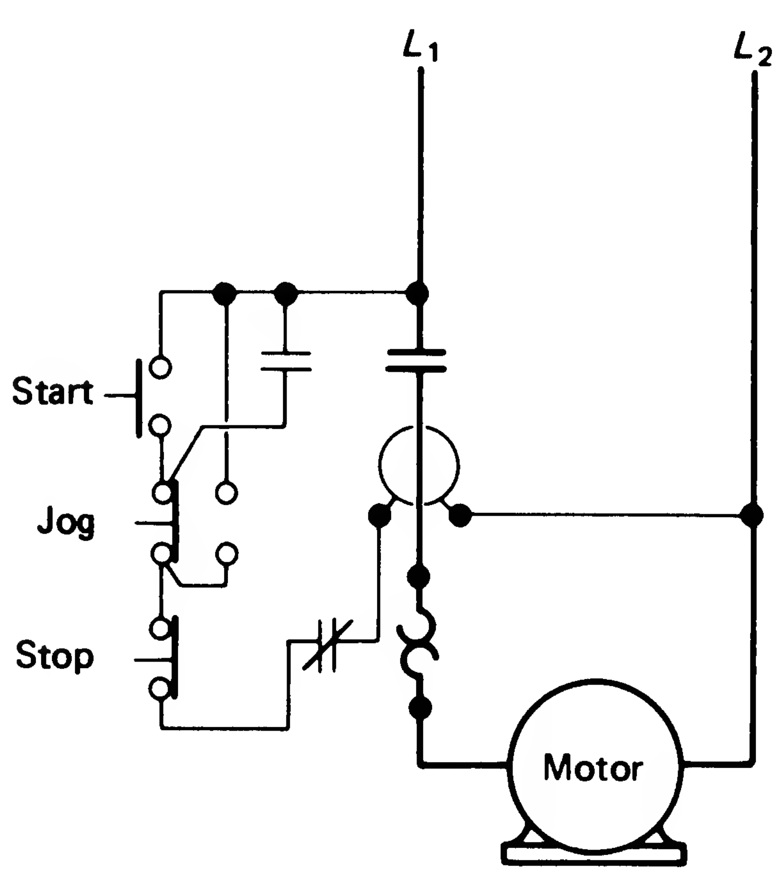


Fig. 7-54. A small dc motor connected to a starter and START-JOG-STOP station.

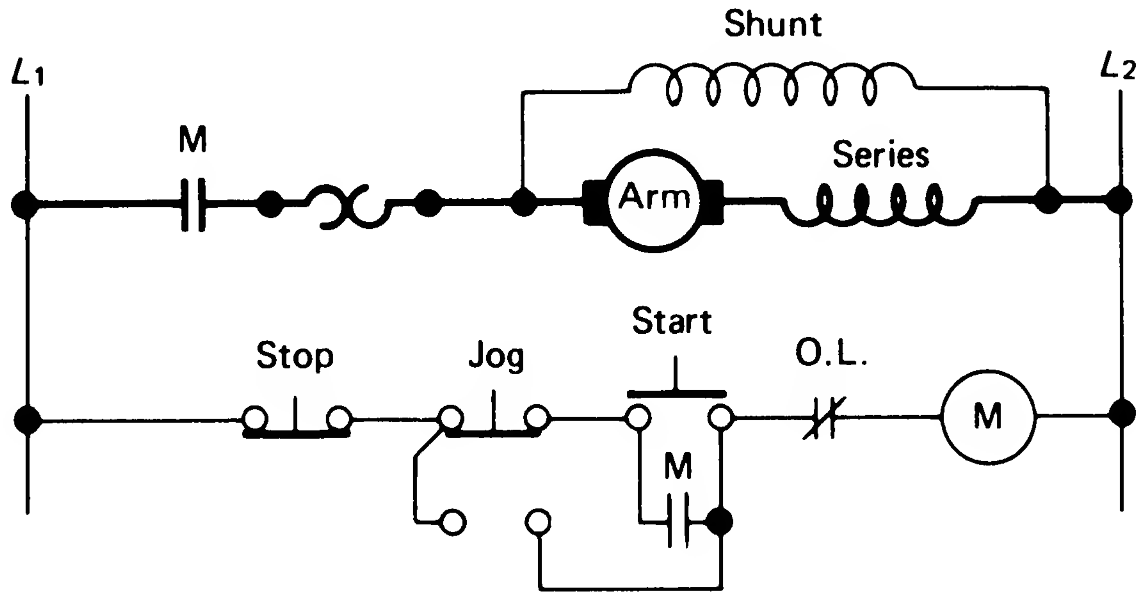


Fig. 7-55. An elementary diagram of a small motor connected to a dc starter and START-JOG-STOP station.

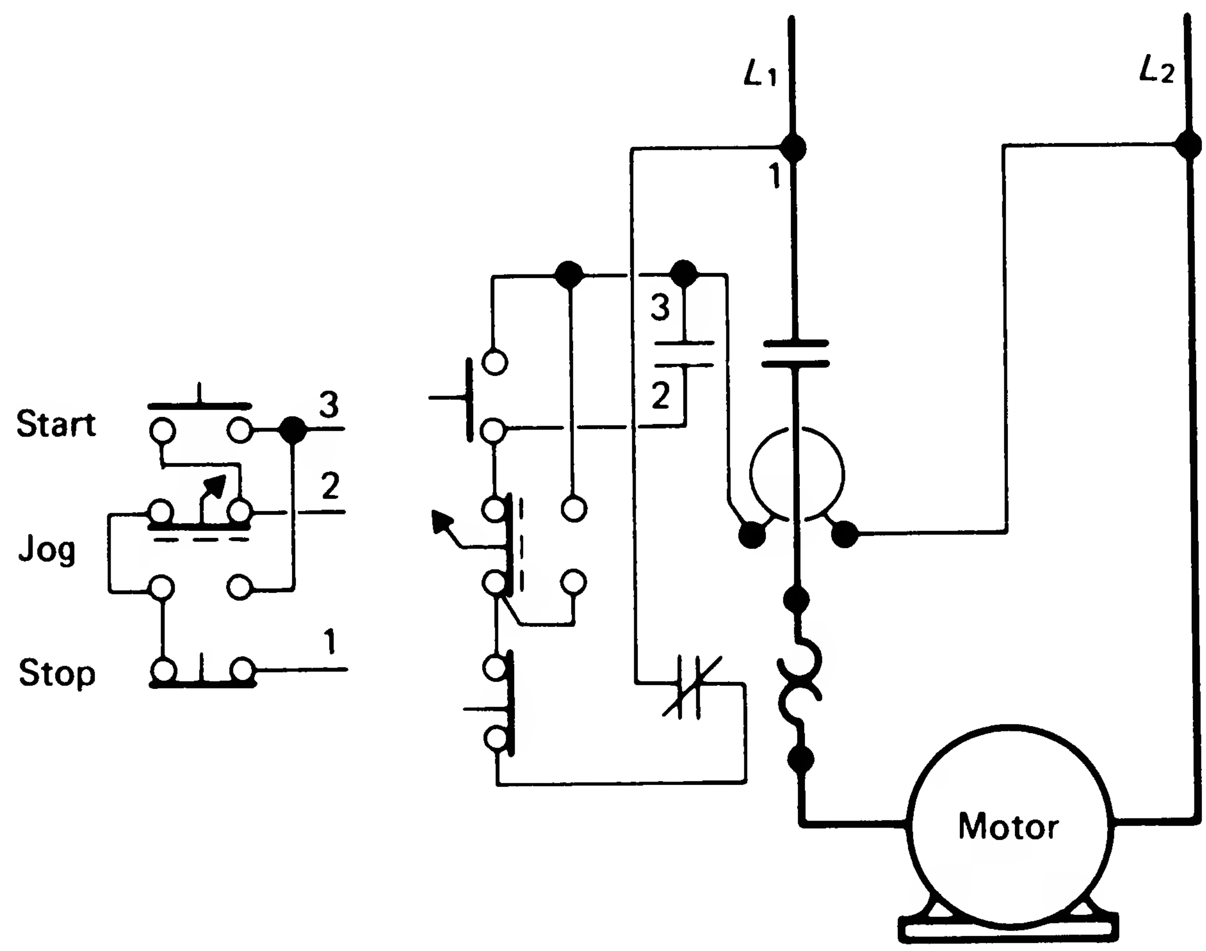


Fig. 7-56. A small dc motor connected to a starter and station with a JOG selector push button.

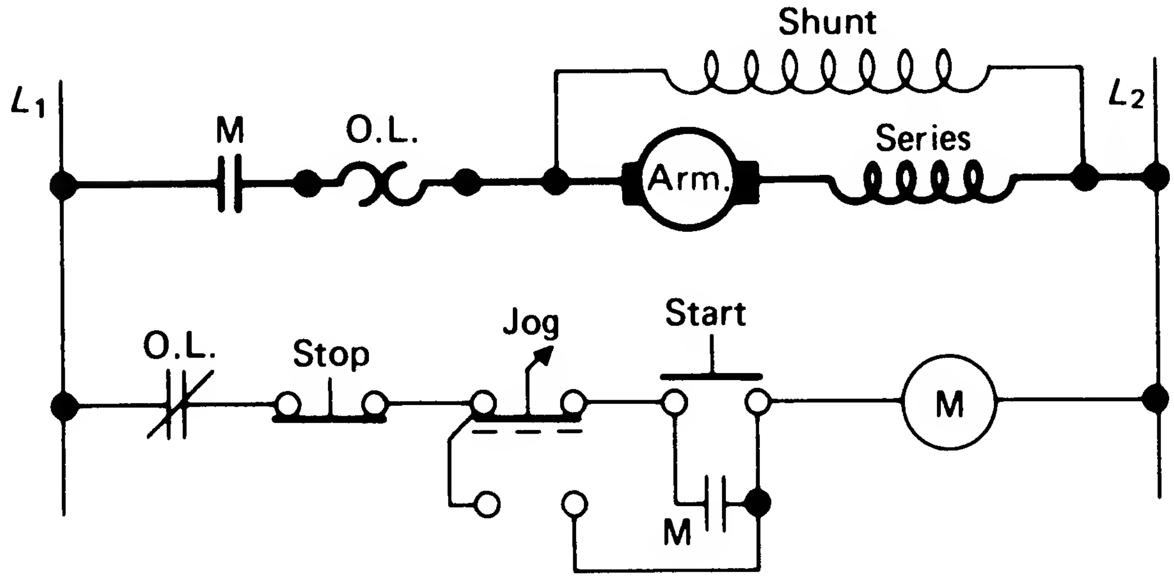


Fig. 7-57. START-JOG-STOP station with selector push button.

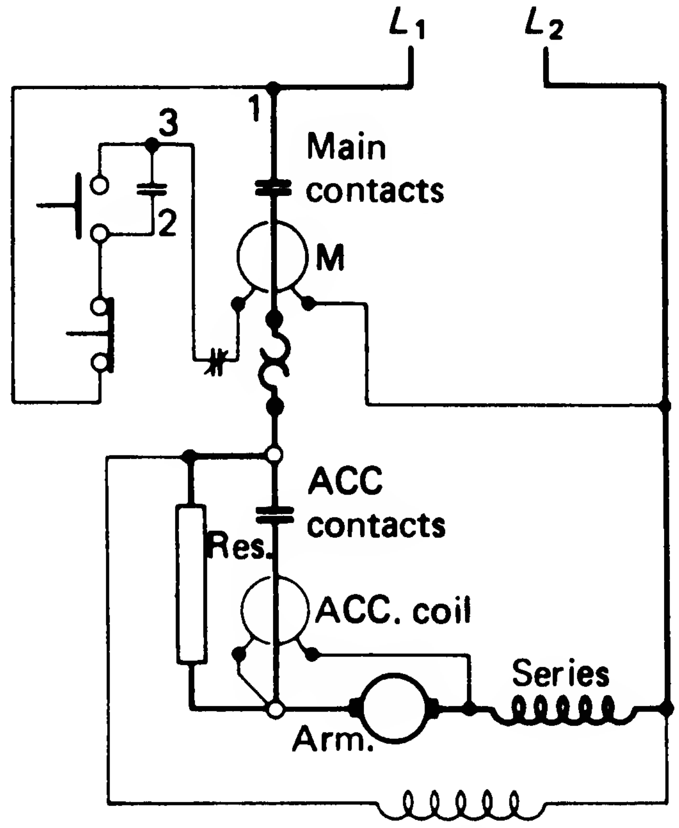


Fig. 7-58. Diagram of a simple counter e.m.f. starter operated by a magnetic switch.

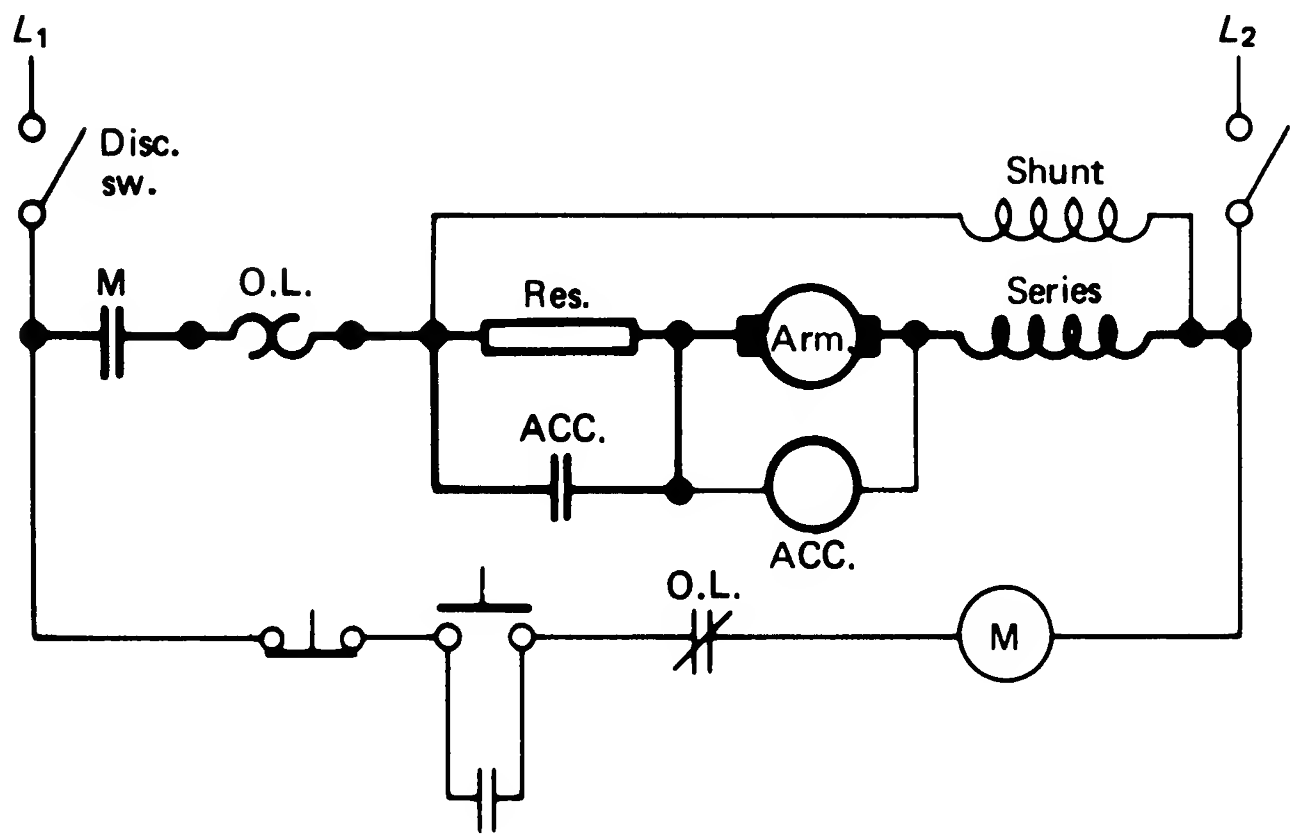


Fig. 7-59. An elementary diagram of a counter e.m.f. starter connected to a compound motor.

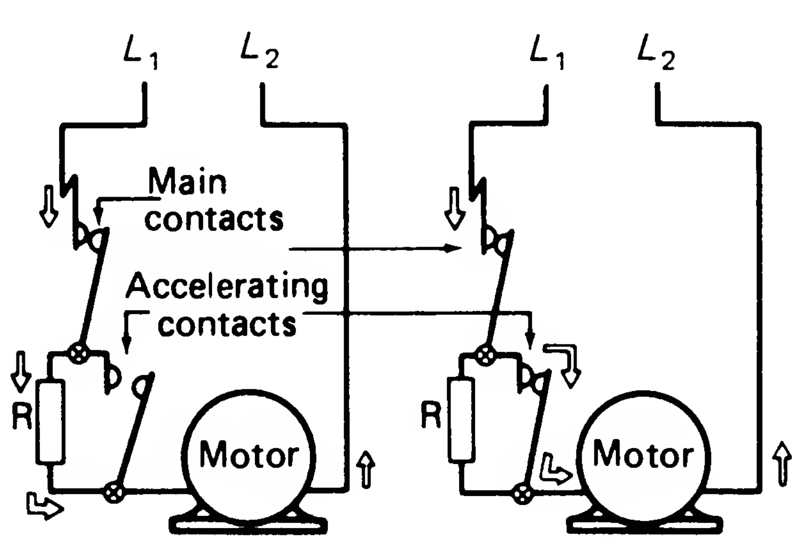


Fig. 7-60. Positions of the accelerating contact of a counter e.m.f. starter when the motor starts and after acceleration.

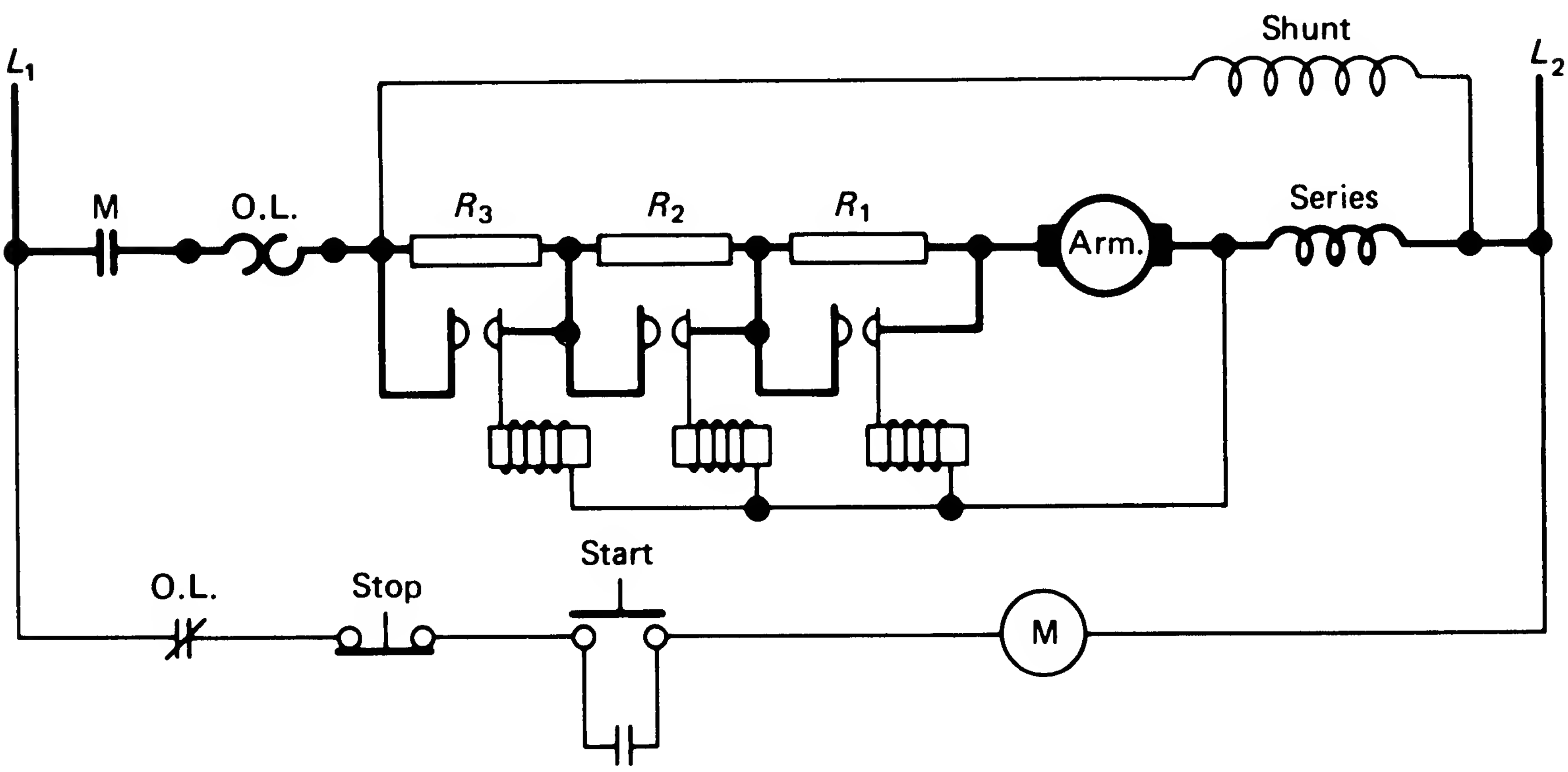


Fig. 7-61. A counter e.m.f. starter with three steps of acceleration connected to a compound motor.

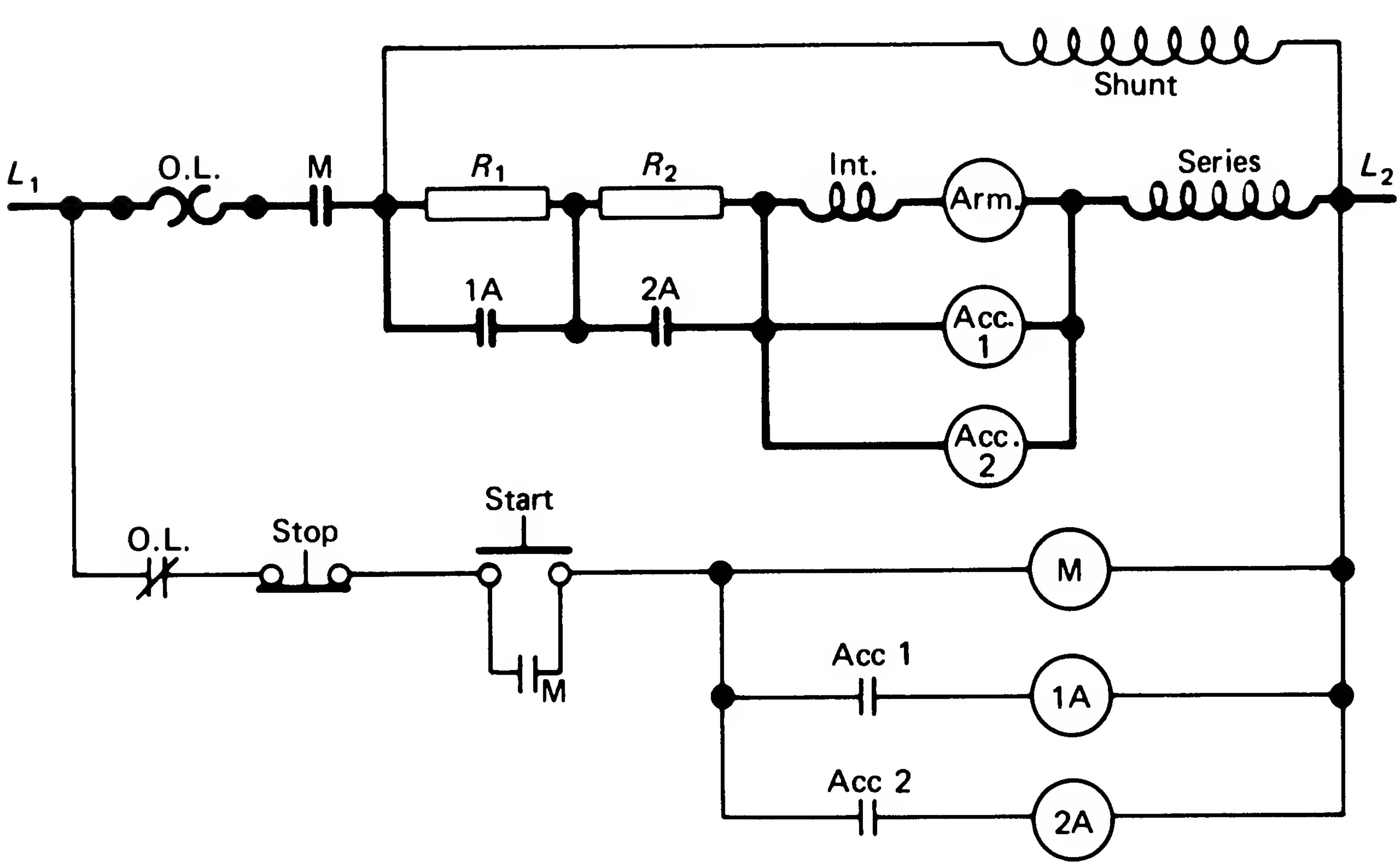


Fig. 7-62. Counter e.m.f. starter using relays.

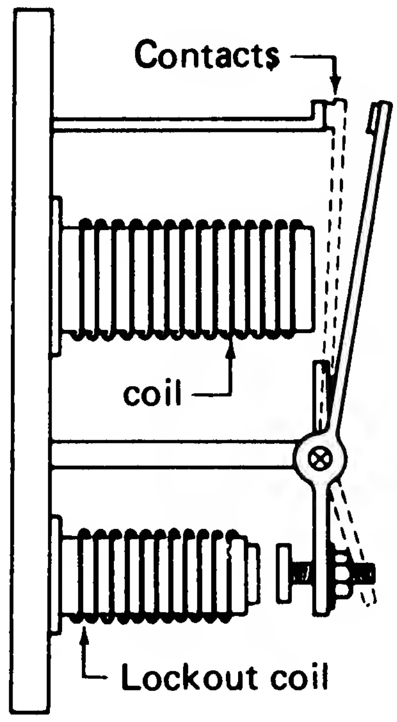


Fig. 7-63. A two-coil lockout contactor used in current-limit starters.

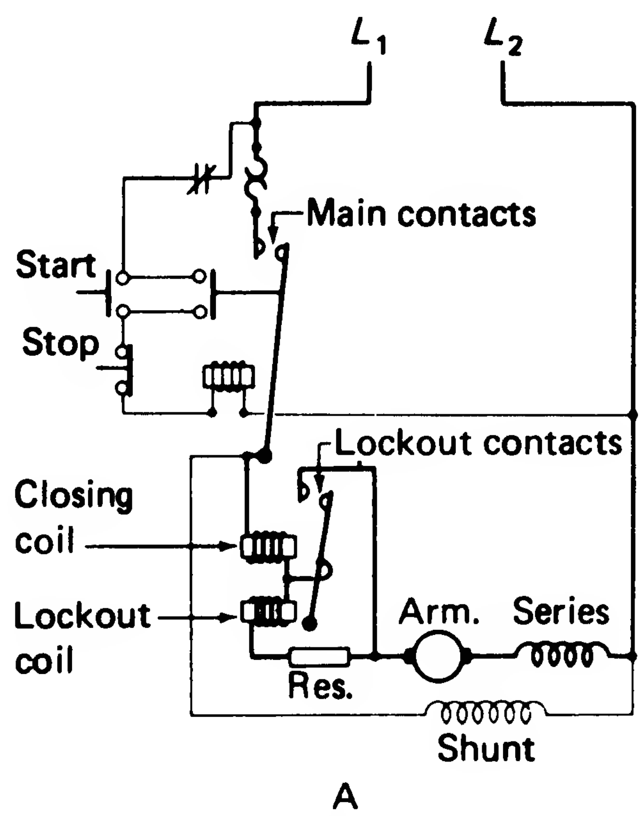


Fig. 7-64a. A two-coil lockout starter with one step of acceleration connected to a compound motor.

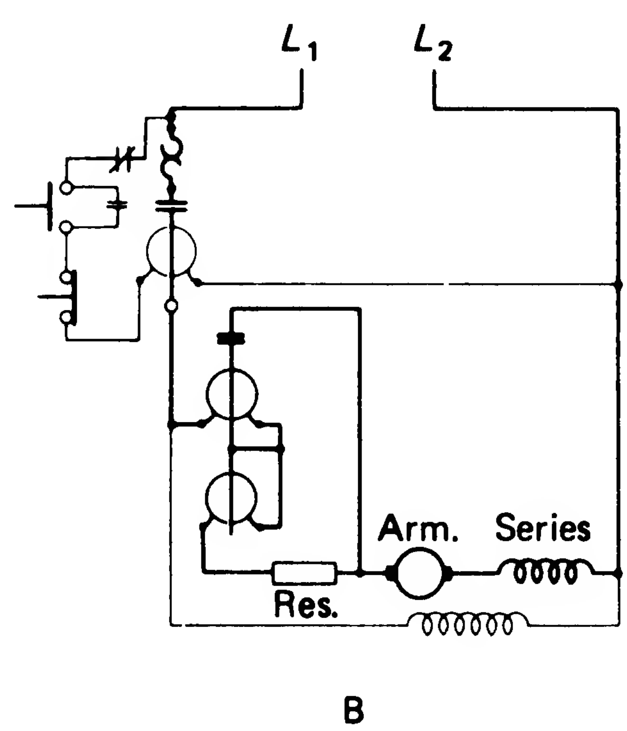


Fig. 7-64b. Different representation of a two-coil lockout starter with one step of acceleration connected to a compound motor.

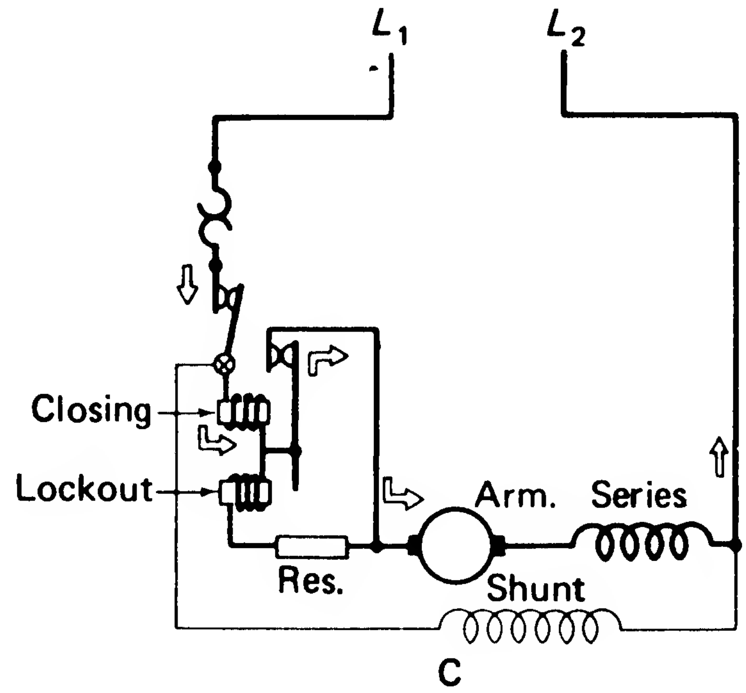


Fig. 7-64c. Position of the accelerating contact of a two-coil lockout starter when a motor is drawing normal current.

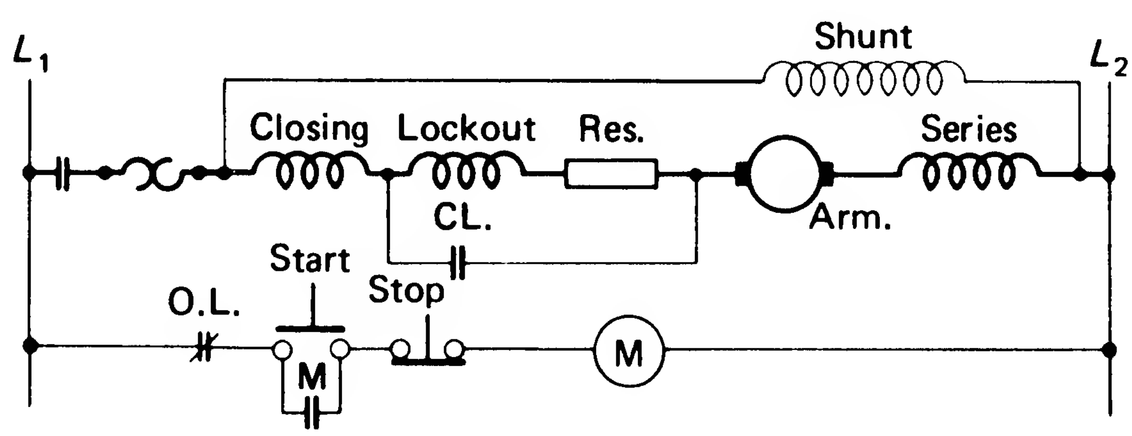


Fig. 7-65. An elementary diagram of a two-coil lockout starter connected to a compound motor.

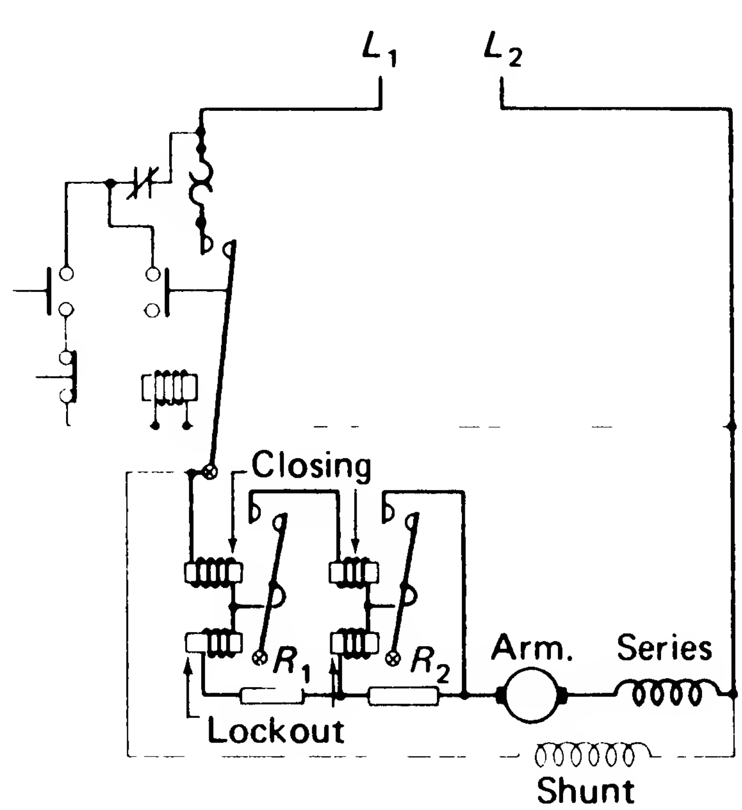


Fig. 7-66. A two-coil lockout controller with two steps of acceleration.

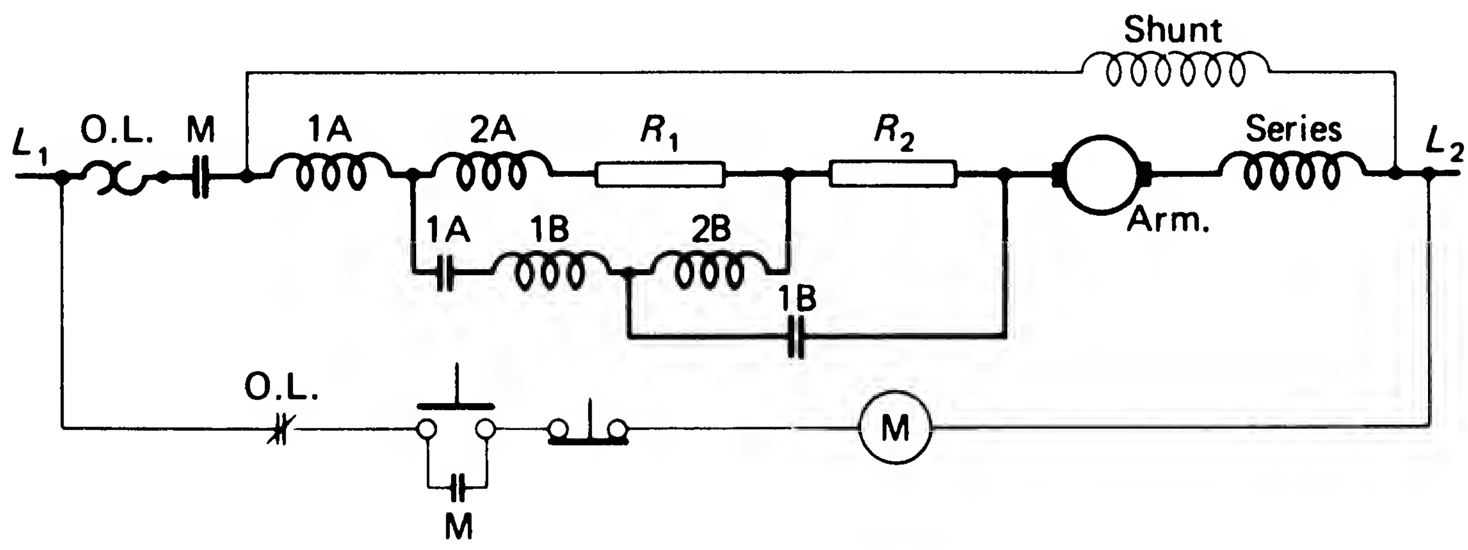


Fig. 7-67. An elementary diagram of a two-step, two-coil lockout starter connected to a compound motor.

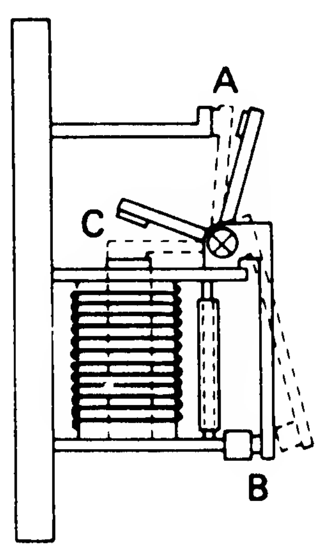


Fig. 7-68. A single-coil lockout contactor.

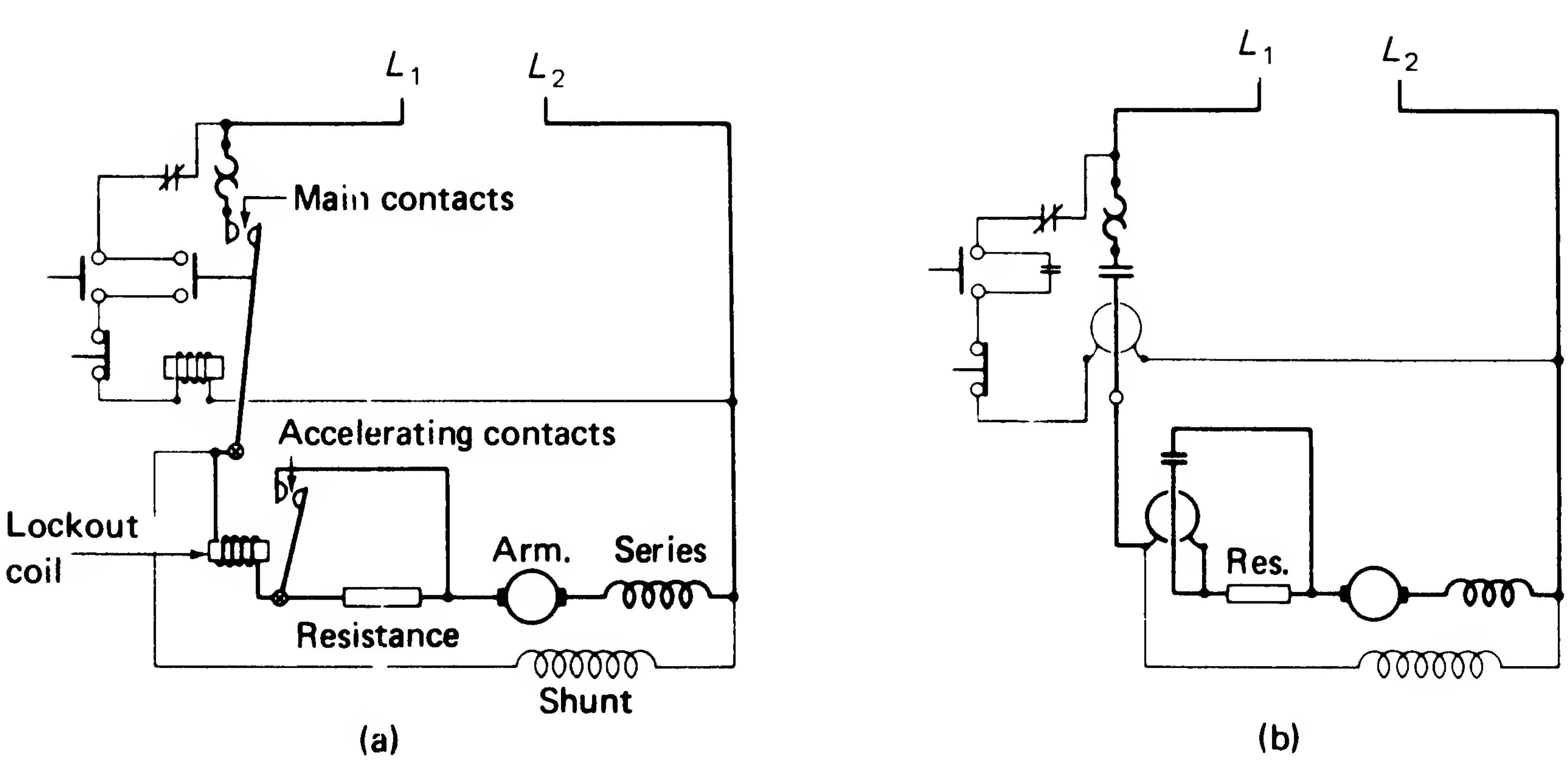


Fig. 7-69. Different representations of a single-coil lockout starter with one step of acceleration connected to a compound motor.

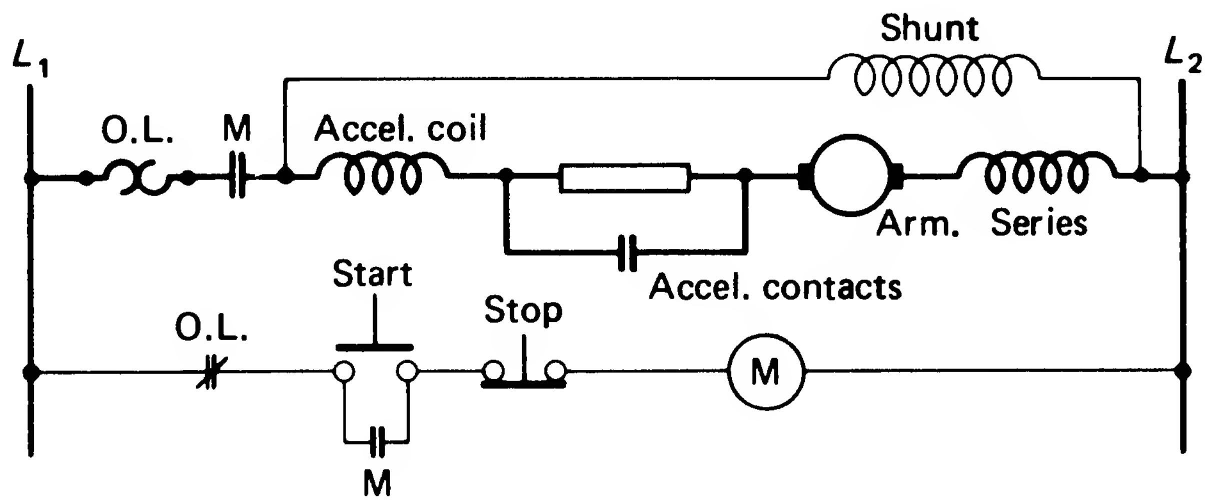


Fig. 7-70. An elementary diagram of a single-coil lockout starter connected to a compound motor.

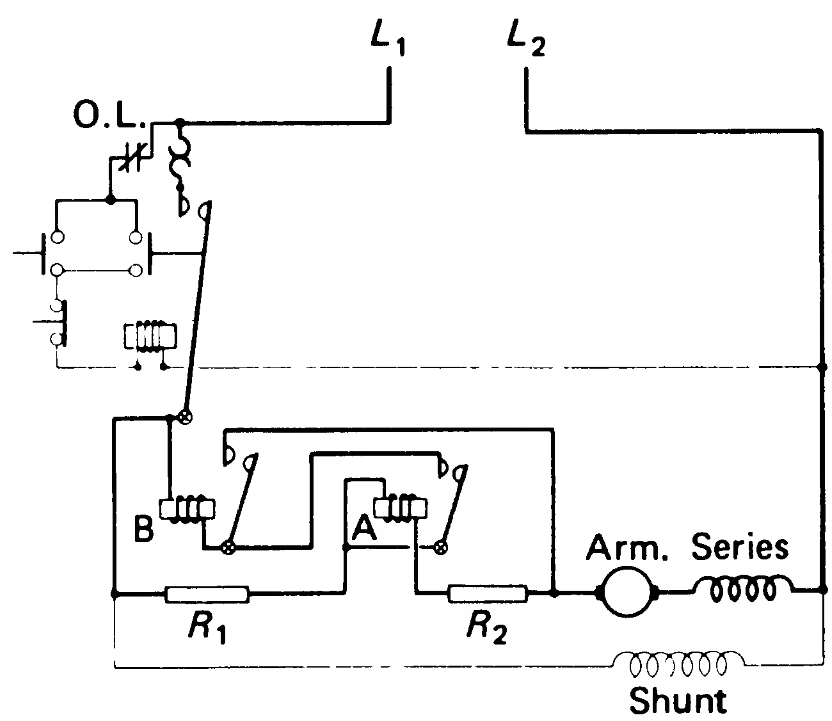


Fig. 7-71. A single-coil lockout starter with two steps of acceleration.

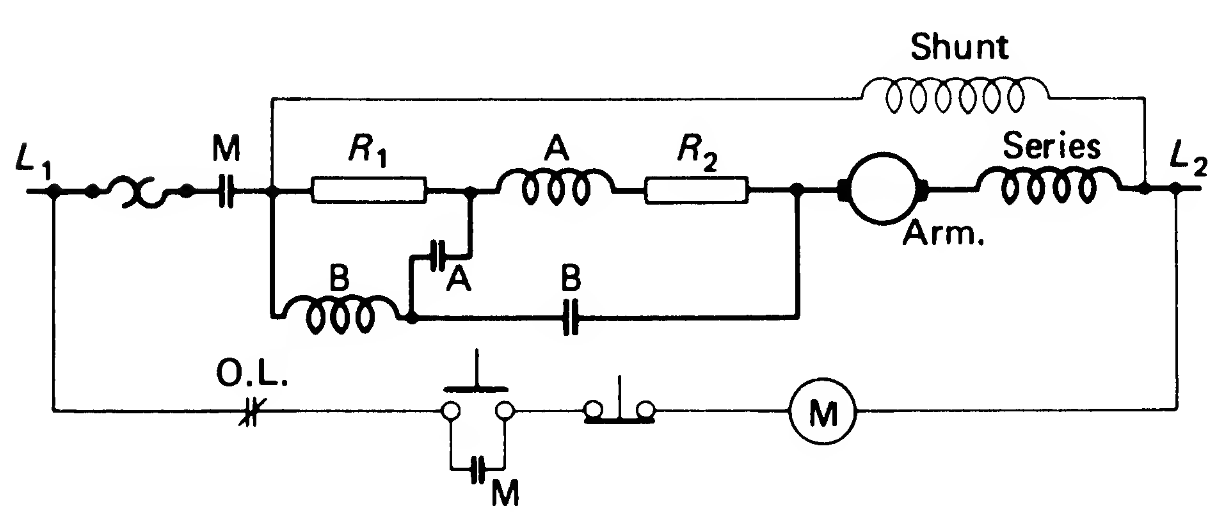


Fig. 7-72. A simplified diagram of **Fig. 7-71.**

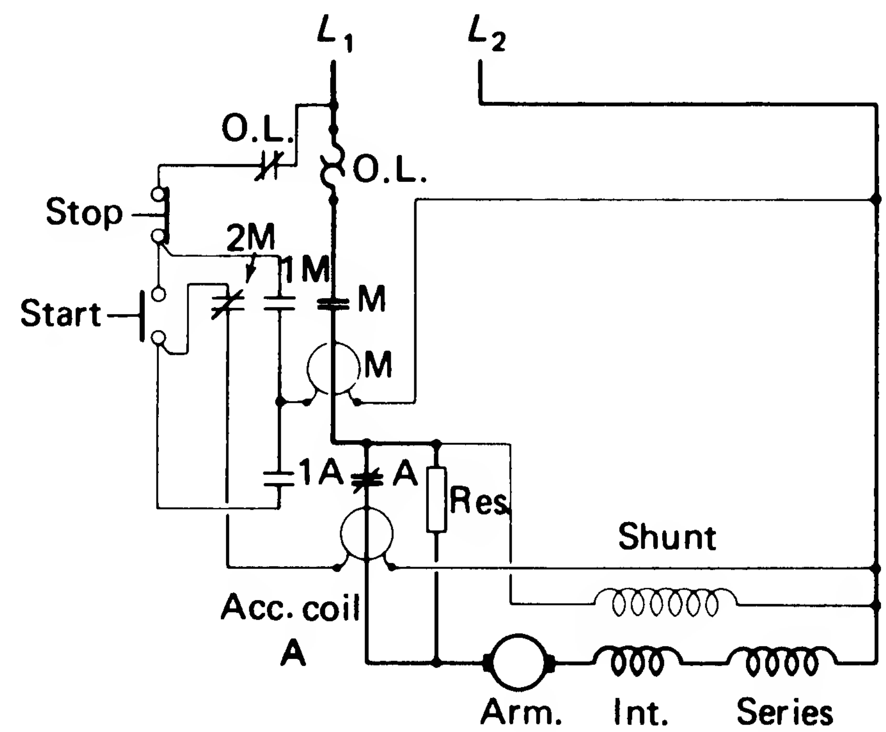


Fig. 7-73. A wiring diagram of a definite magnetic time starter connected to a compound motor.

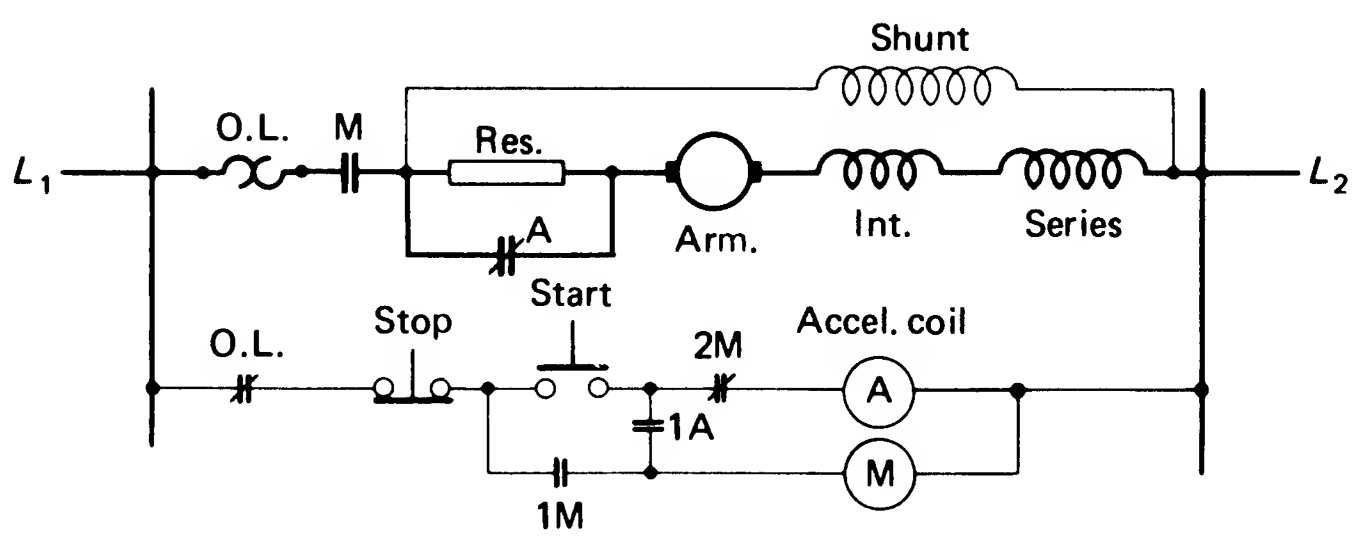


Fig. 7-74. An elementary diagram of the connection of **Fig. 7-73.**

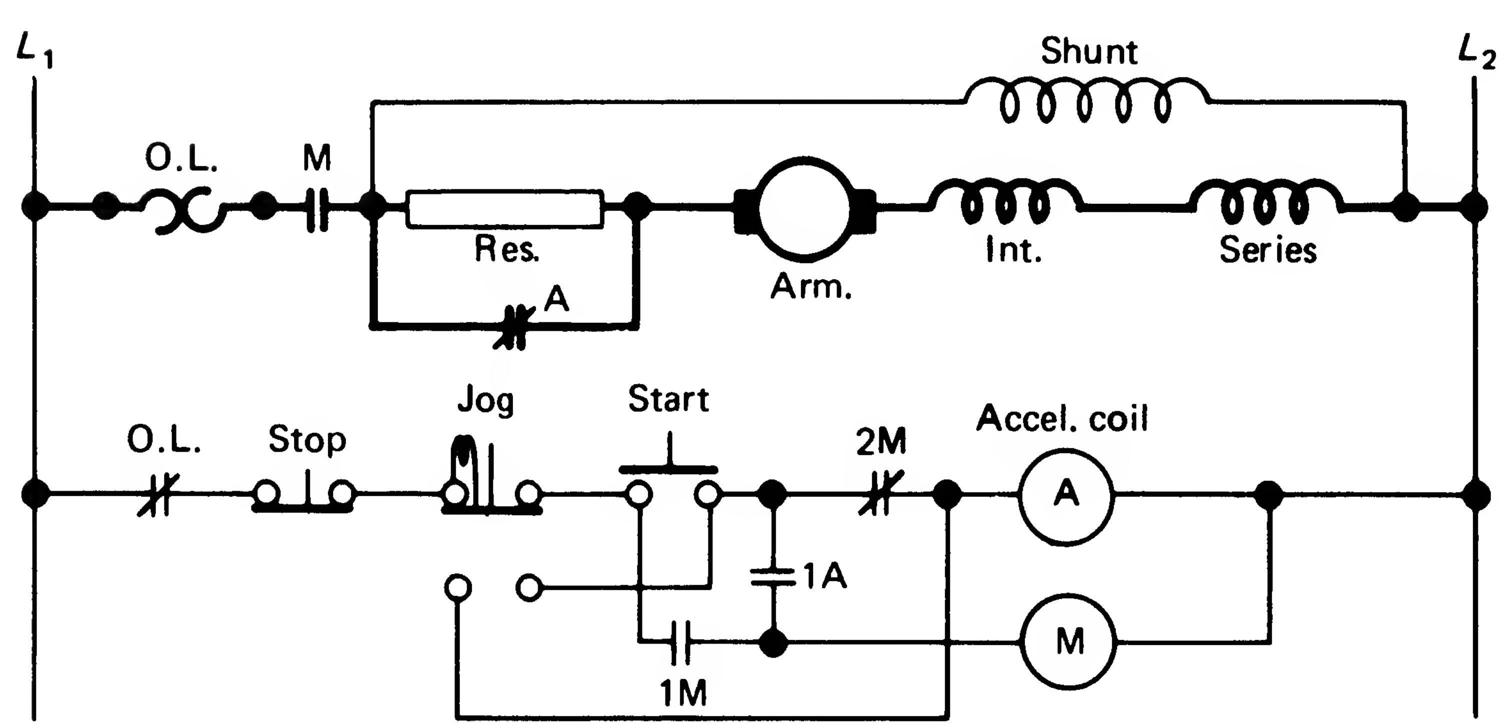


Fig. 7-75. A wiring diagram of a definite magnetic time starter with a START-JOG-STOP station.

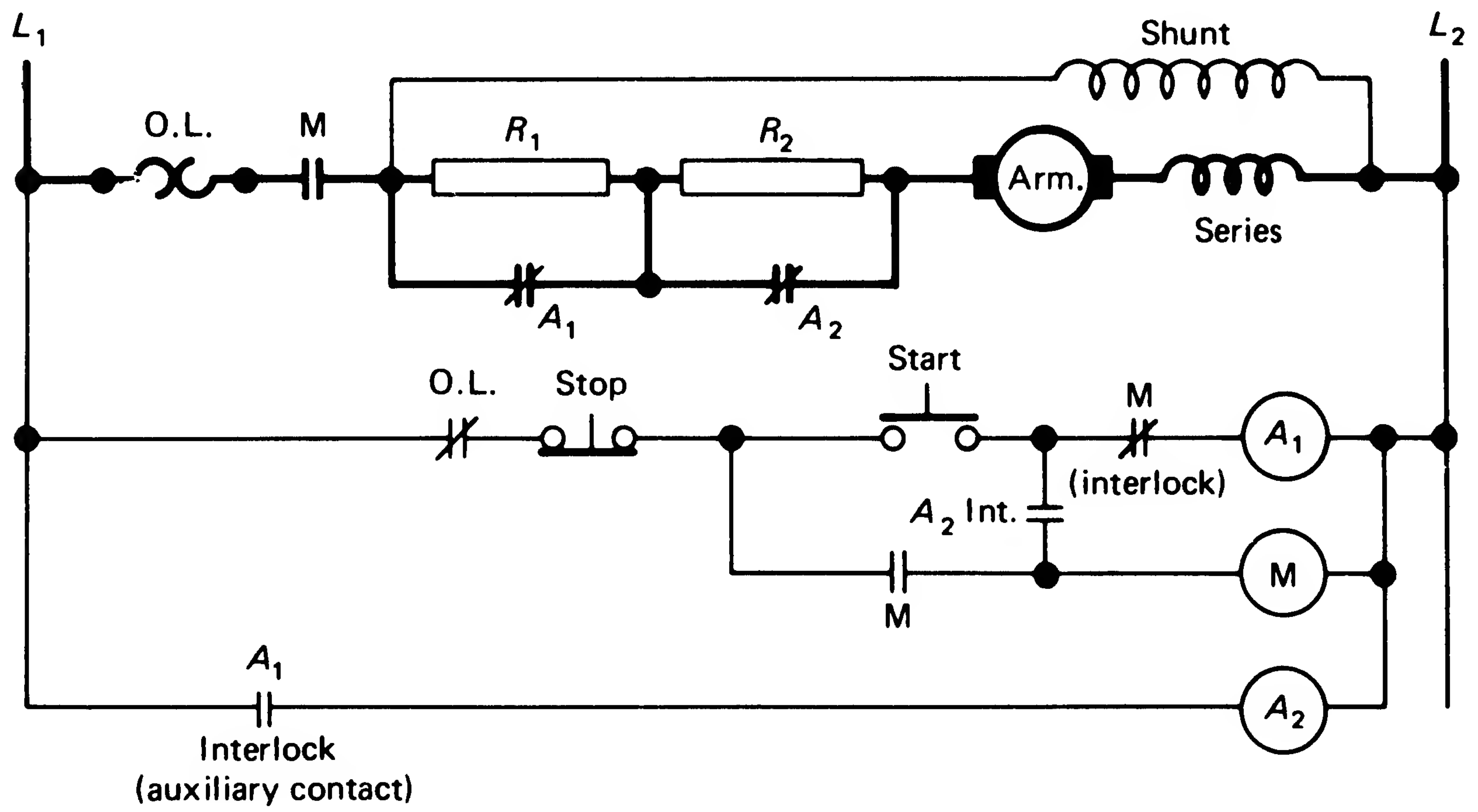


Fig. 7-76. An elementary diagram of a definite magnetic time starter having two steps of resistance.

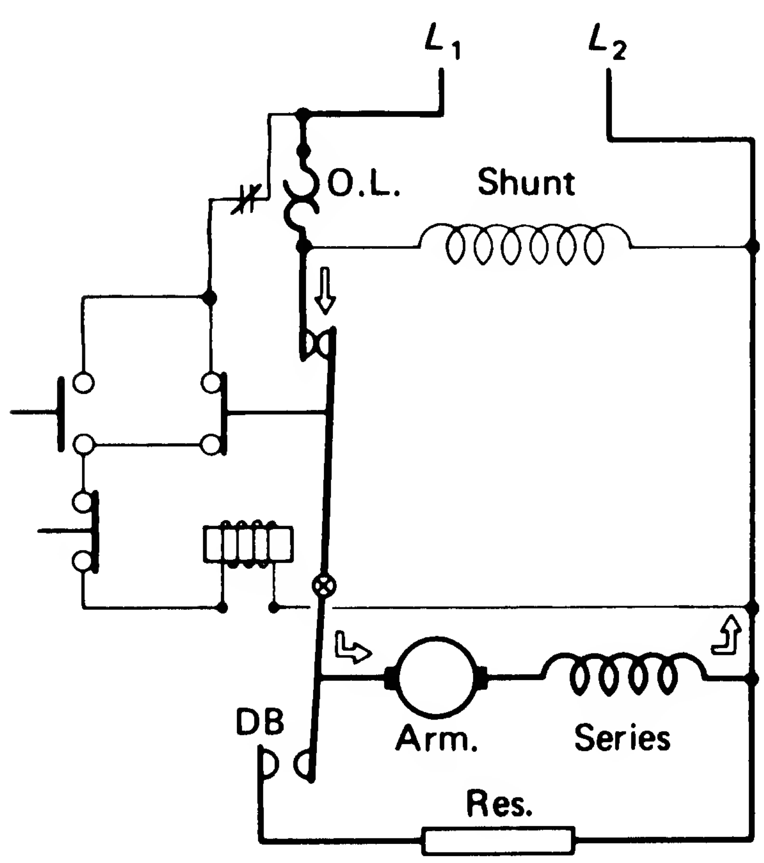


Fig. 7-77. A starter equipped with dynamic braking. Contacts are shown in position while motor is operating. Note the flow of current in the armature.

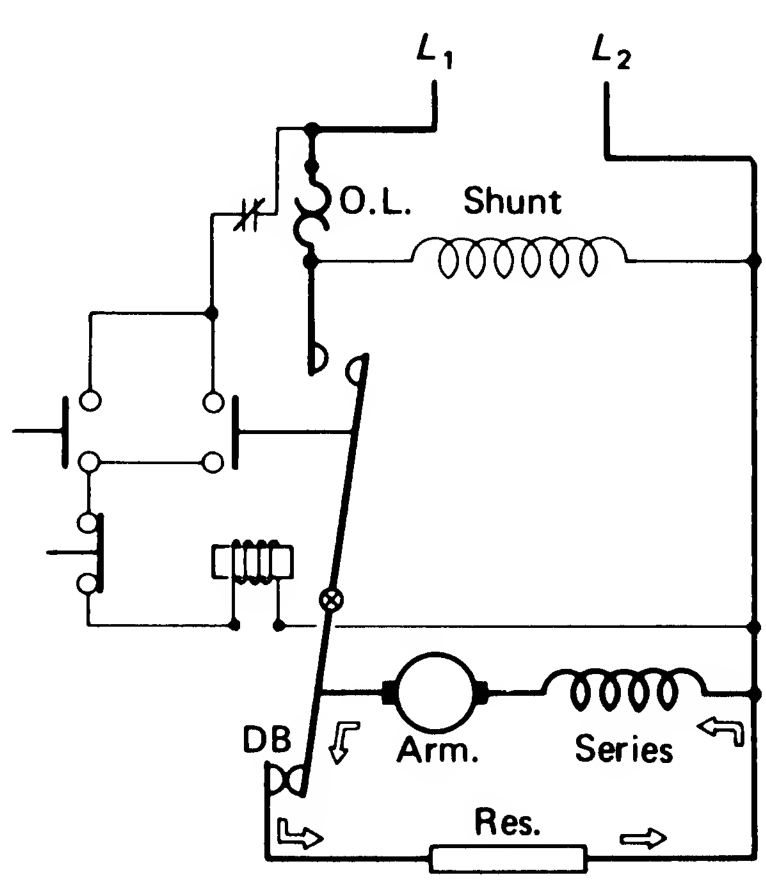


Fig. 7-78. Position of the dynamic braking contacts when the current is shut off.

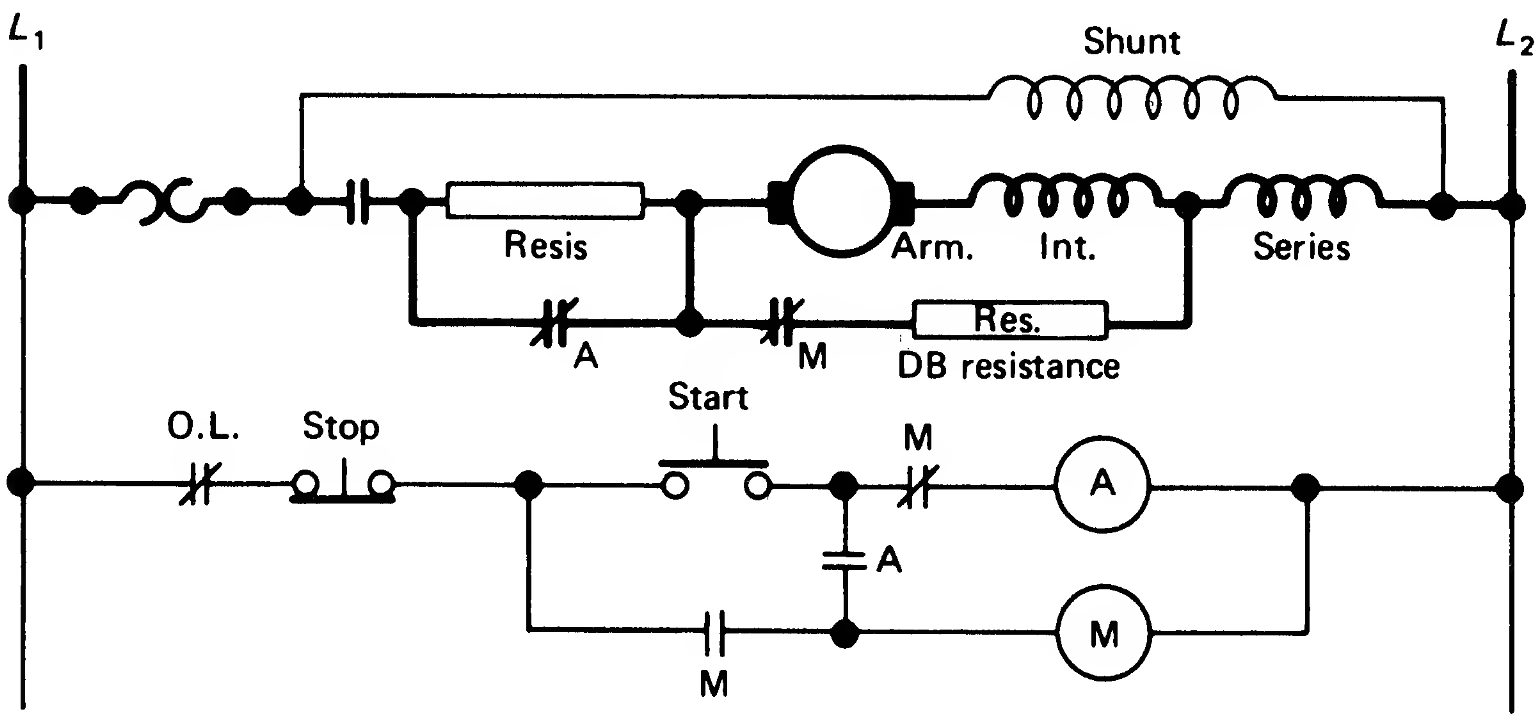


Fig. 7-79. A wiring diagram of a magnetic time delay starter with dynamic braking connected to a compound motor.

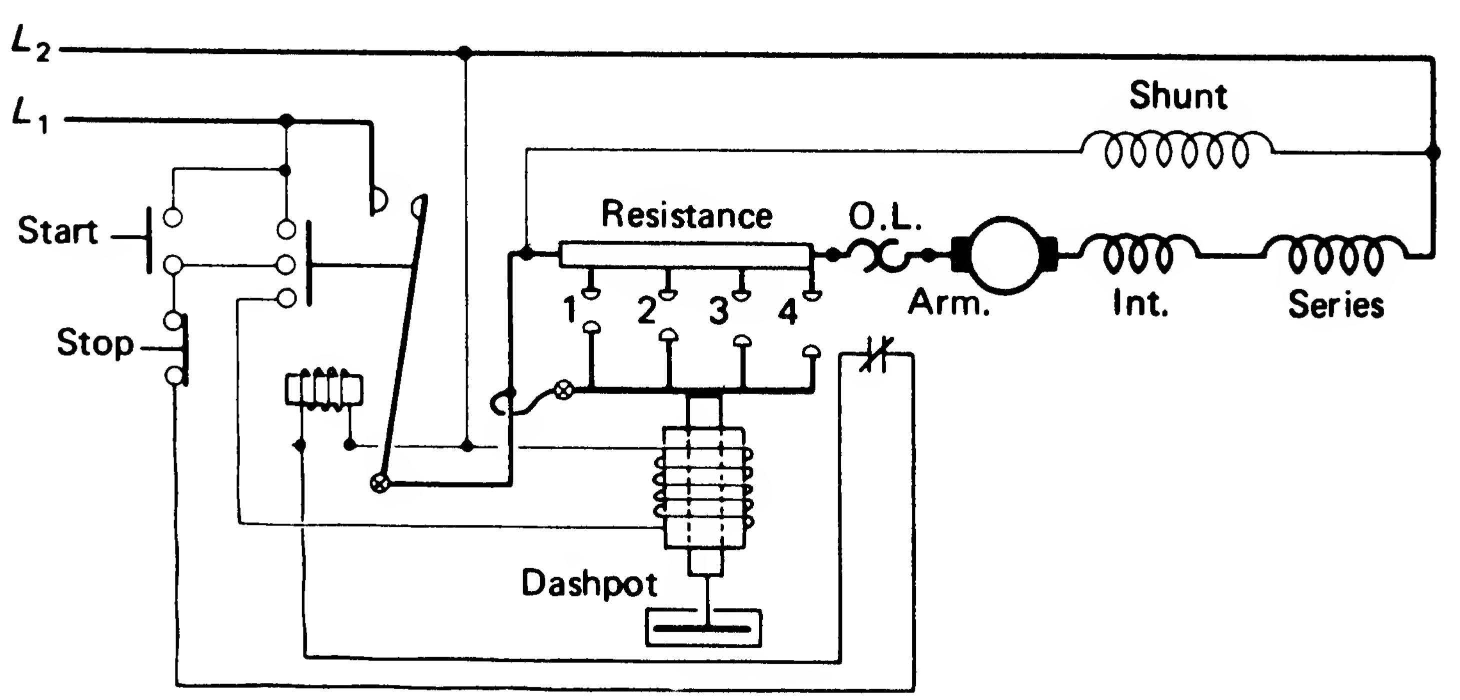


Fig. 7-80. A starter using dashpot acceleration.

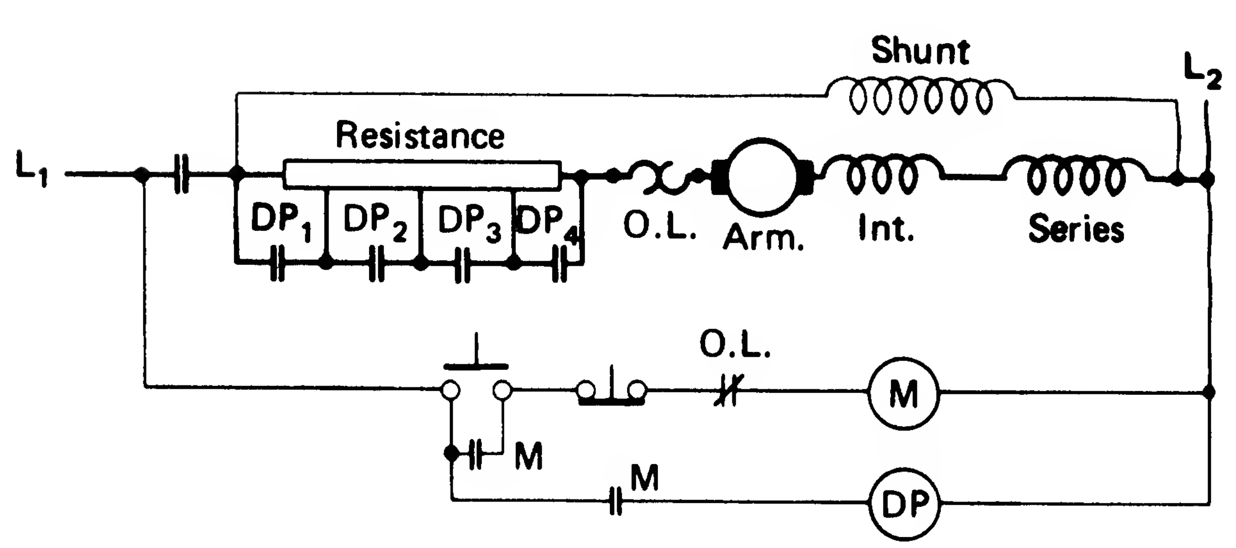


Fig. 7-81. A line diagram of a dashpot starter.

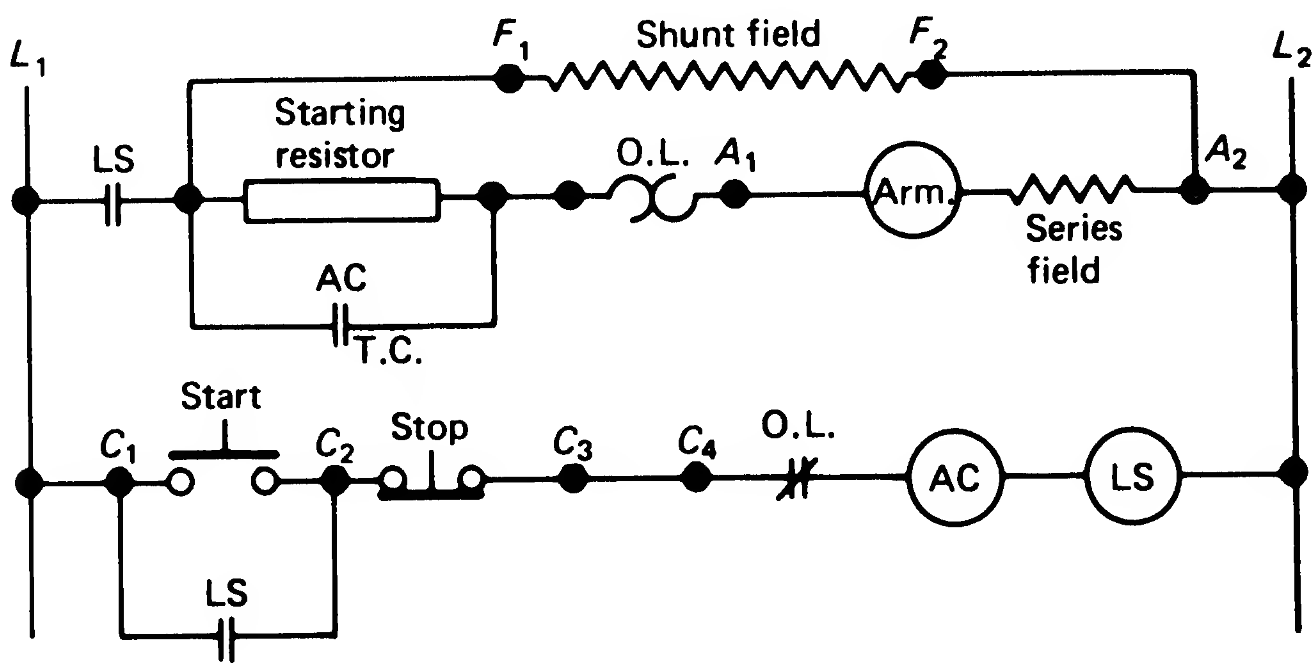


Fig. 7-82. Line diagram of a dc reduced-voltage starter using a fluid dashpot accelerating mechanism. *(Allen-Bradley Co.)*

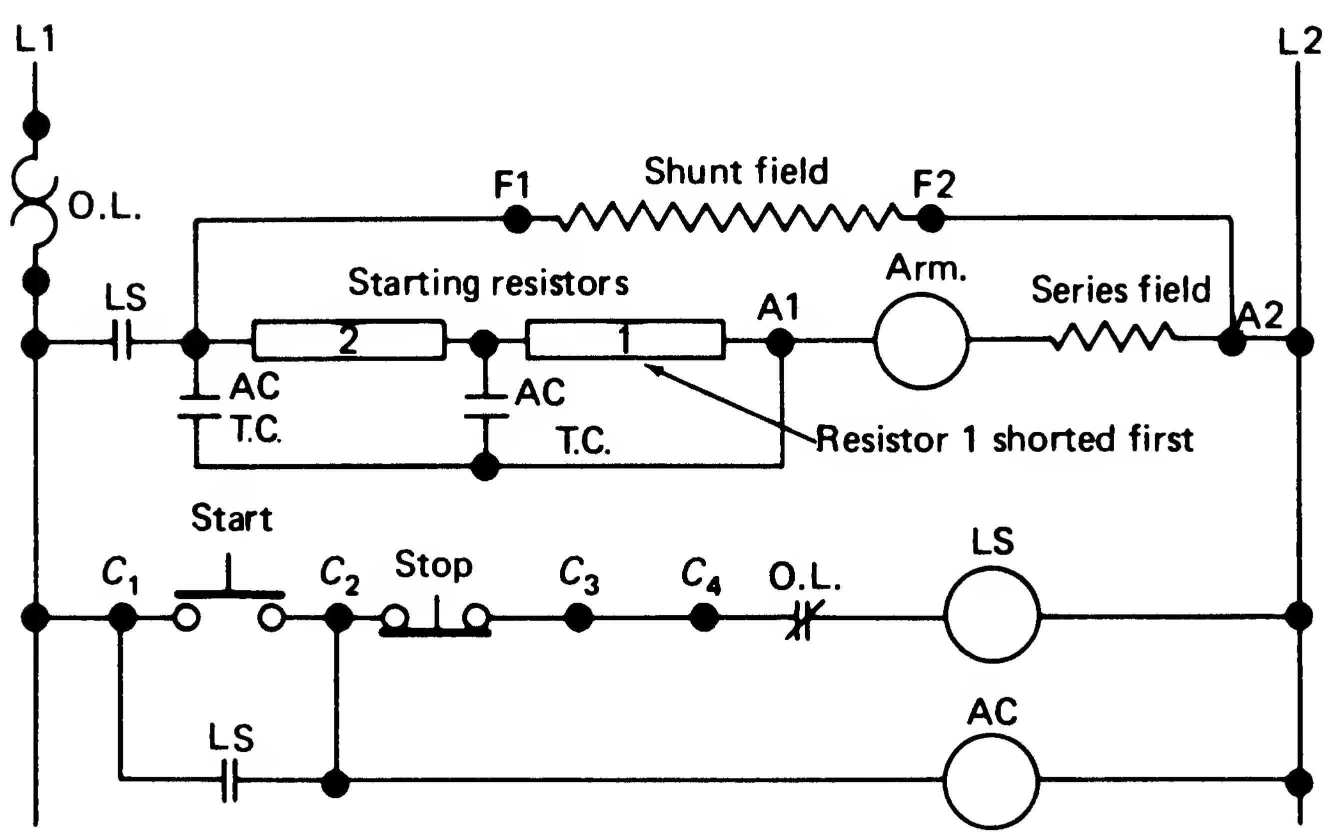


Fig. 7-83. Reduced-voltage starter with two increments of resistance in the circuit. *(Allen-Bradley Co.)*

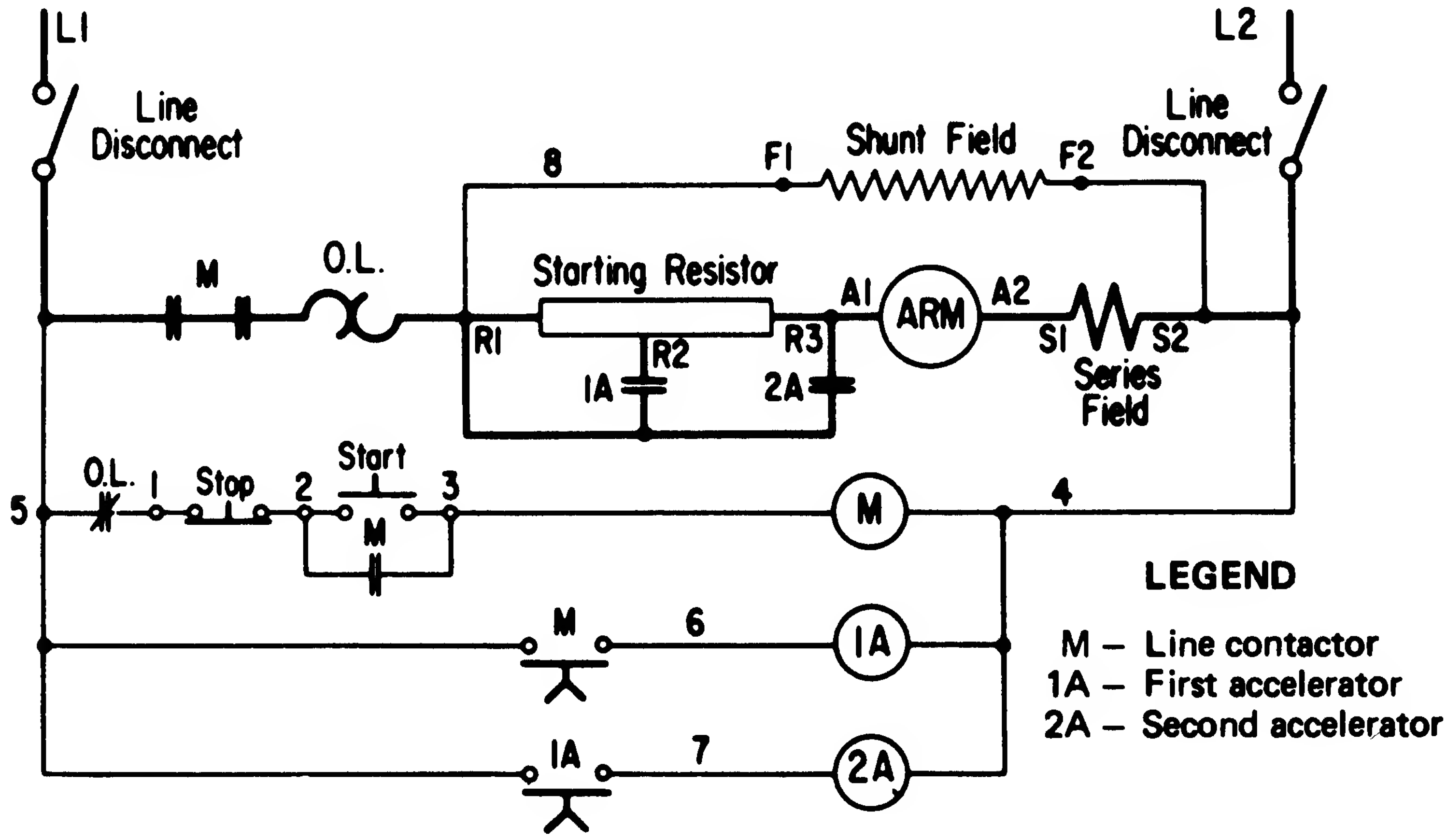


Fig. 7-84. A reduced-voltage starter with time limit acceleration. This starter uses a pneumatic timing mechanism. *(Allen-Bradley Co.)*

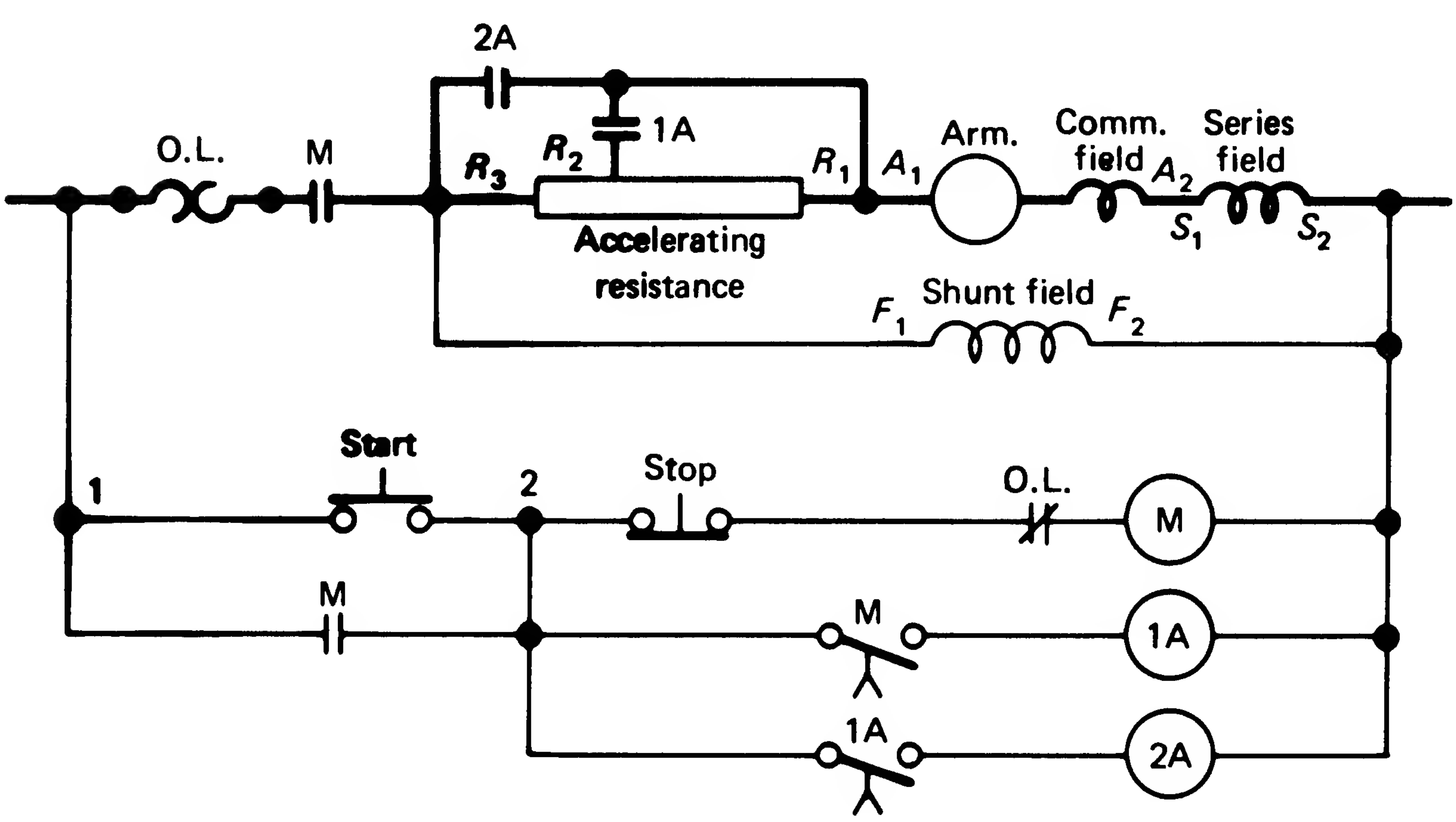


Fig. 7-85. A line diagram of a timed accelerating starter similar to the previous starter.

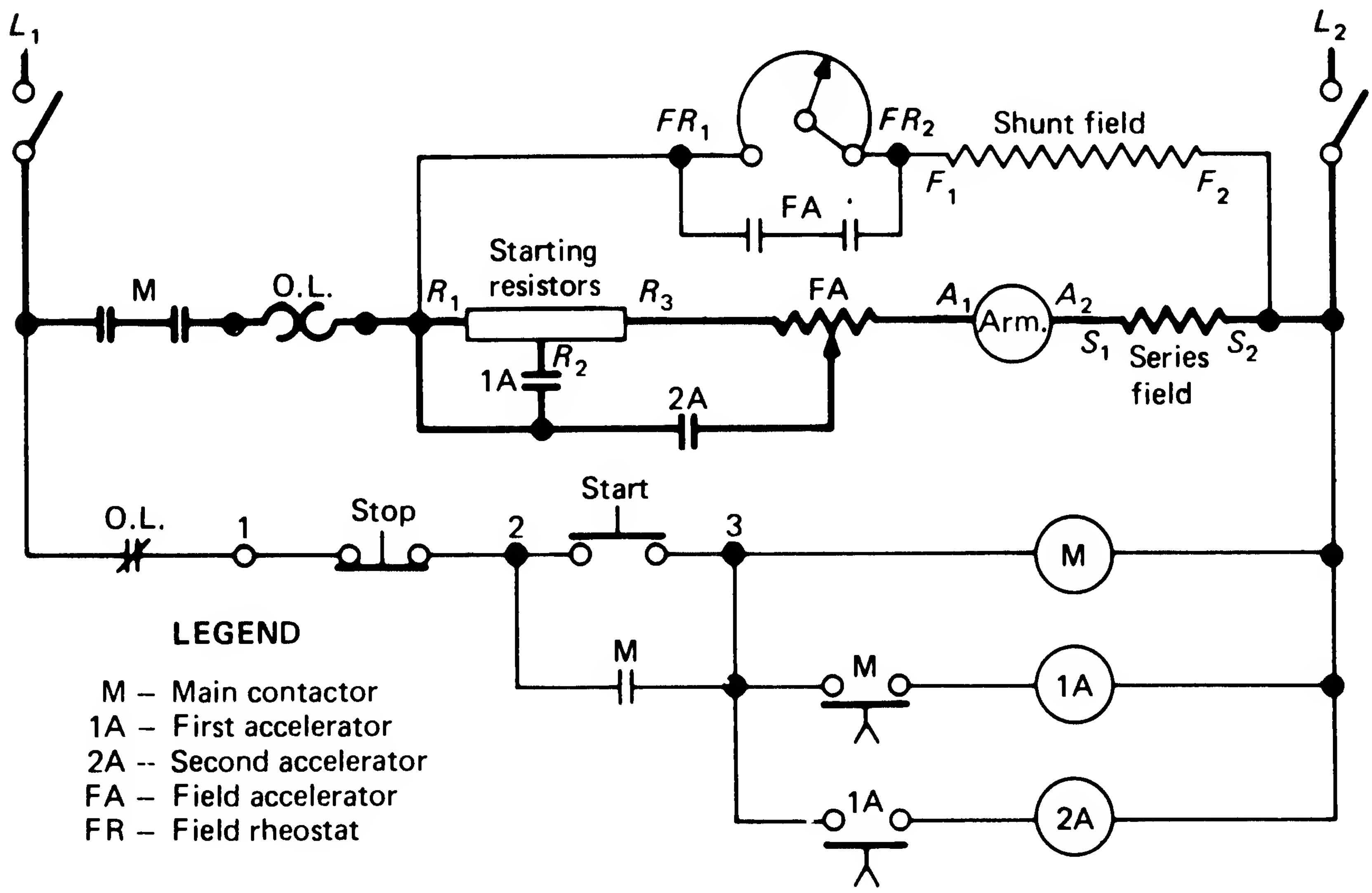


Fig. 7-86. An adjustable speed dc starter with field accelerating relay. *(Allen Bradley Co.)*

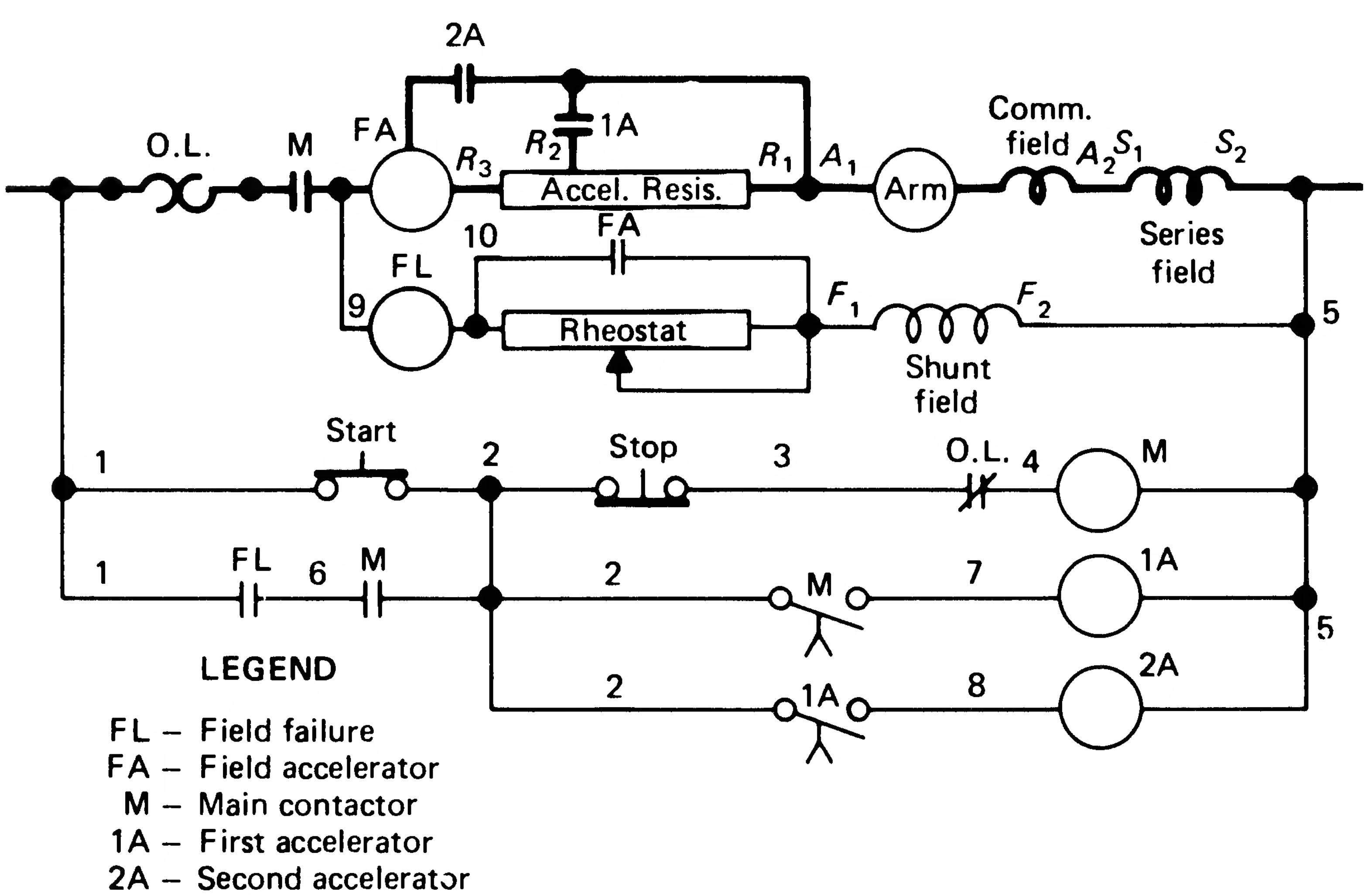


Fig. 7-87. An adjustable speed dc starter with field accelerating relay and field failure relay. *(Square D)*

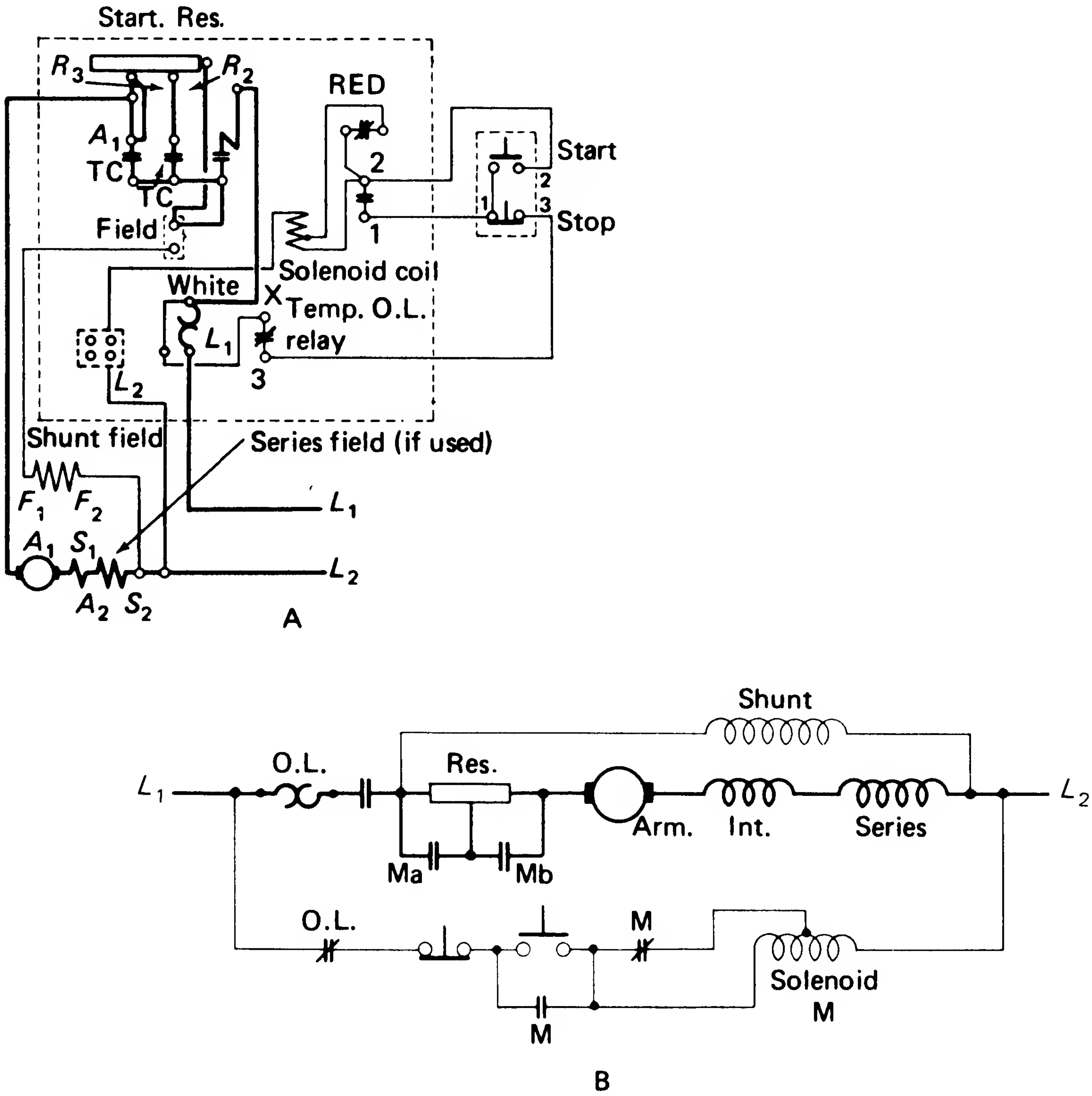


Fig. 7-88a,b. Wiring diagrams of a definite mechanical time starter.

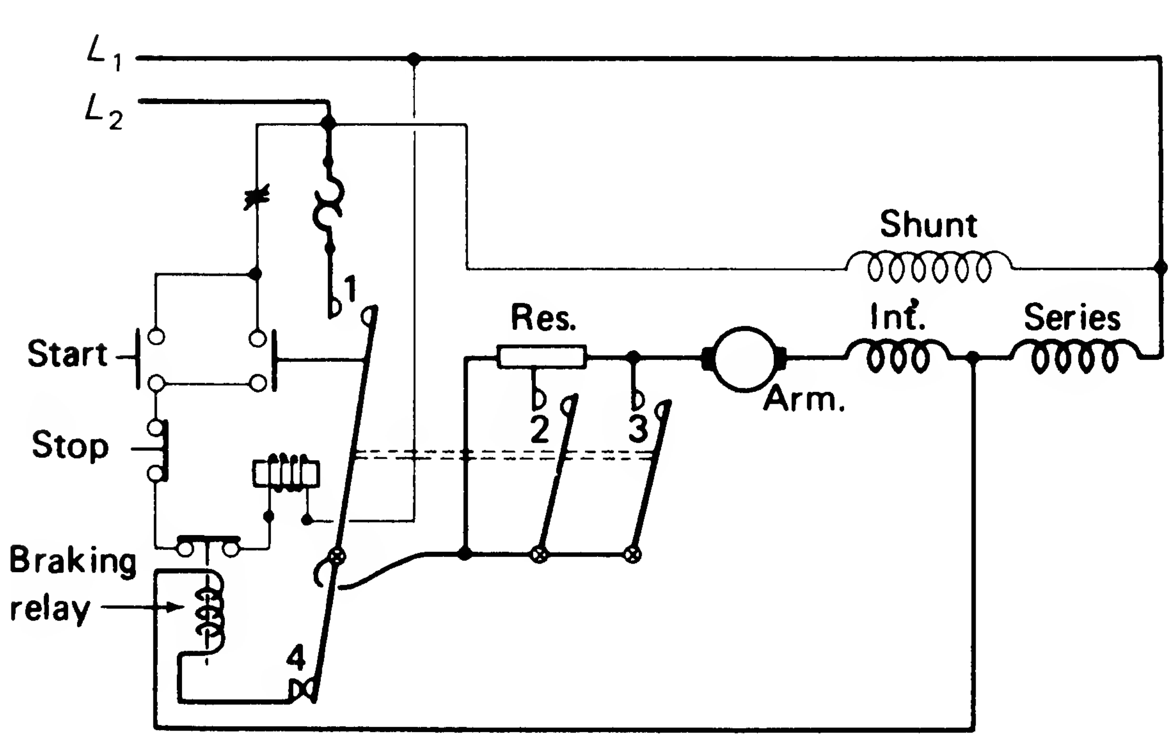


Fig. 7-89. A geared timing starter with dynamic braking.

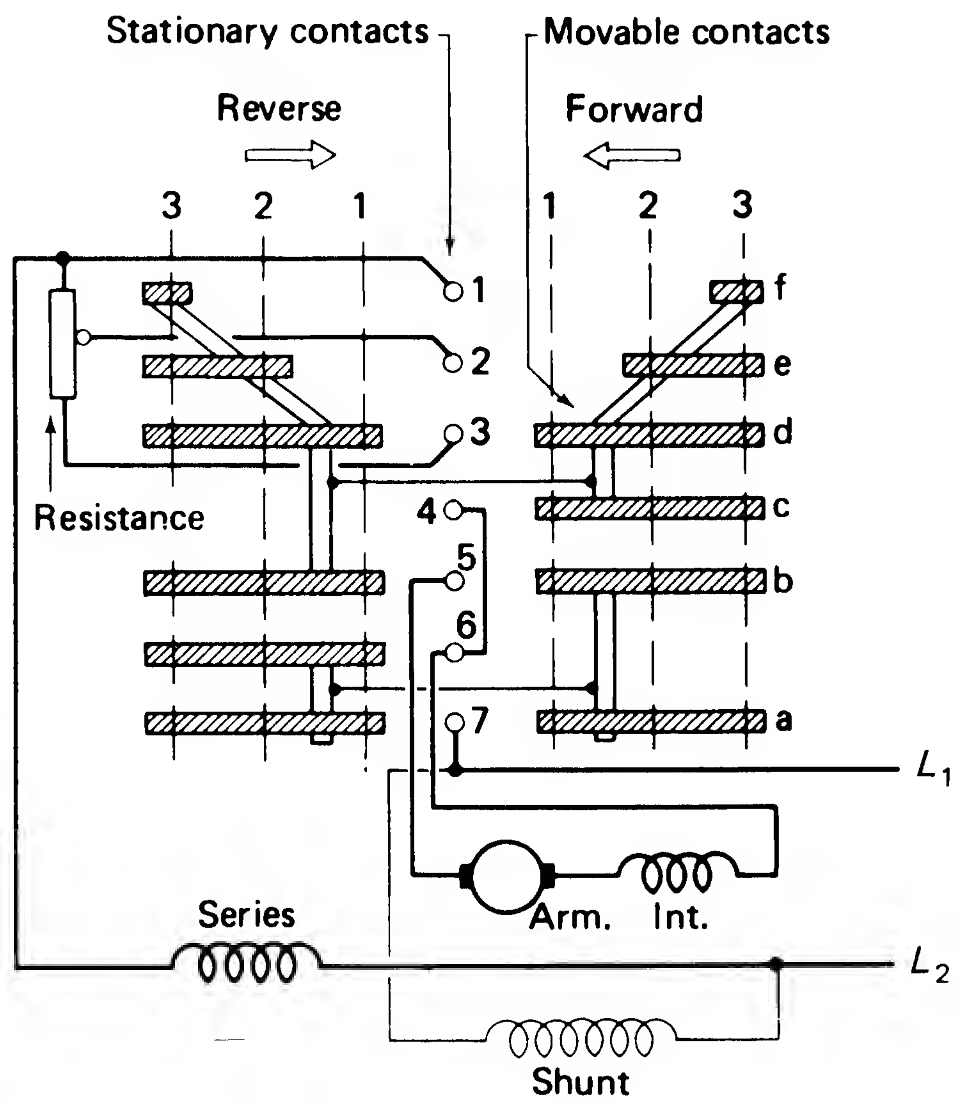


Fig. 7-90. A typical simple type of drum controller connected to compound motor.

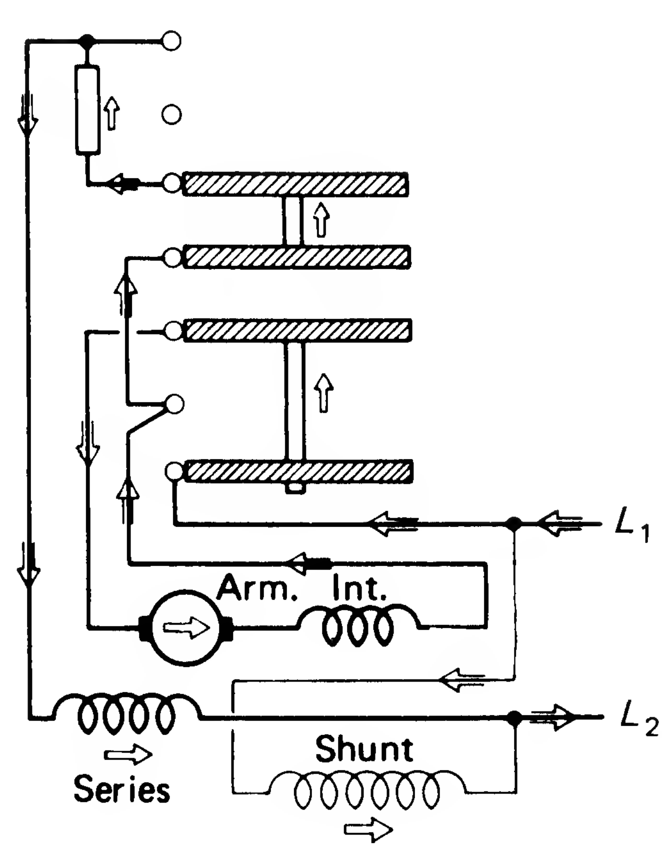


Fig. 7-91. First position of the controller of **Fig. 7-90.**

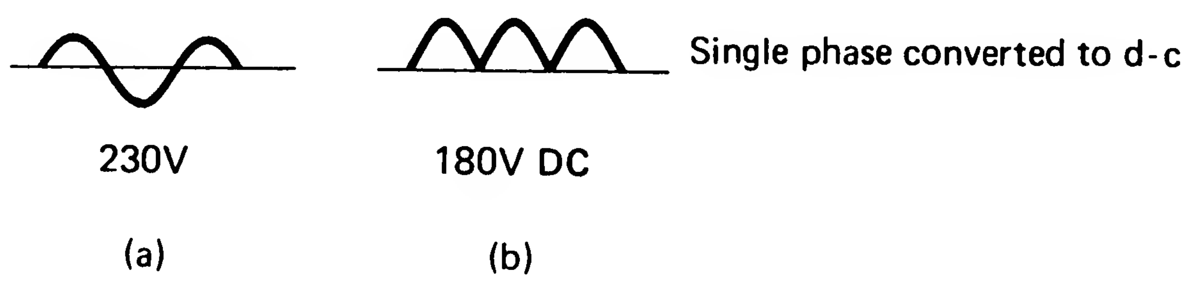


Fig. 7–92. The single-phase sine wave and the way it looks after the controller converts it to dc.

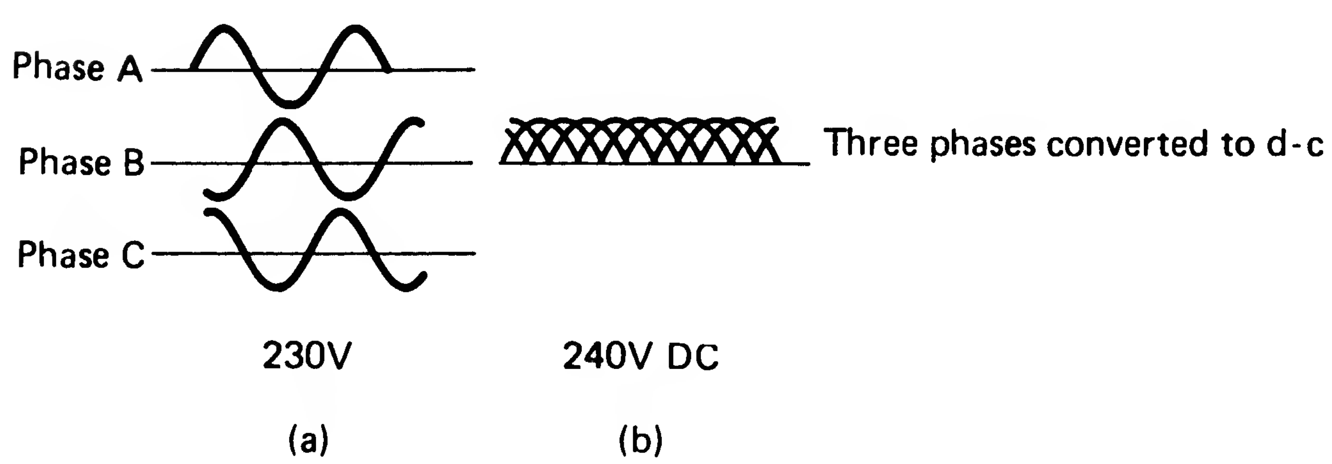


Fig. 7–93. The three separate voltages of the three-phase sine wave and the way they look after the controller converts them to dc.

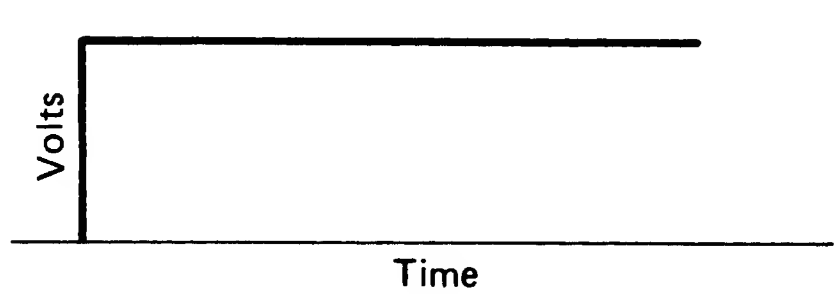


Fig. 7–94. How dc voltage from a battery compares with converted ac. Direct current does not have the ripple effect that converted ac has.

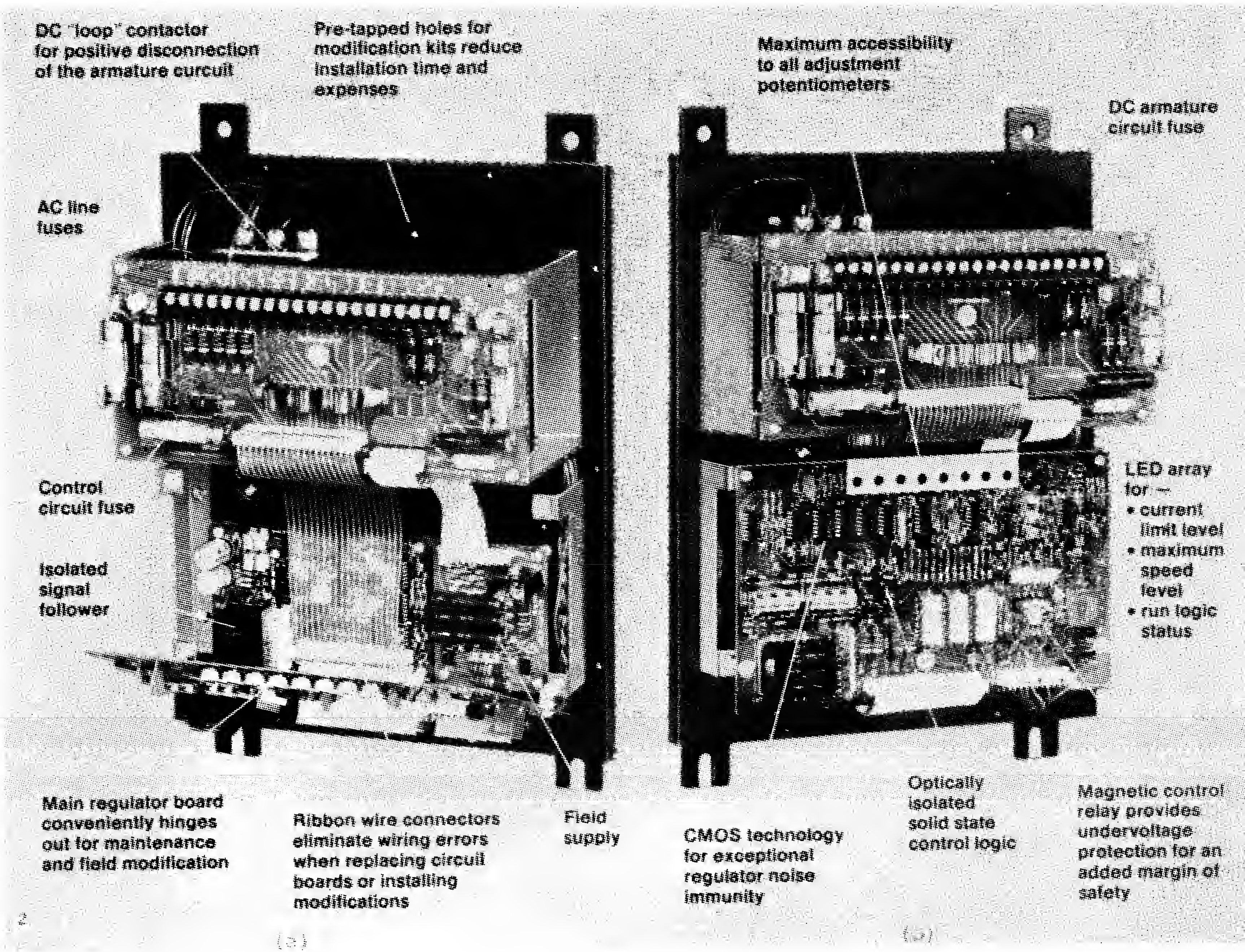


Fig. 7-95. A single-phase-powered, dc drive showing (a) the regulator board hinged open to show the location of some of the circuitry and (b) with the regulator board in place. The upper half is the power circuitry. *(Allen-Bradley Co.)*

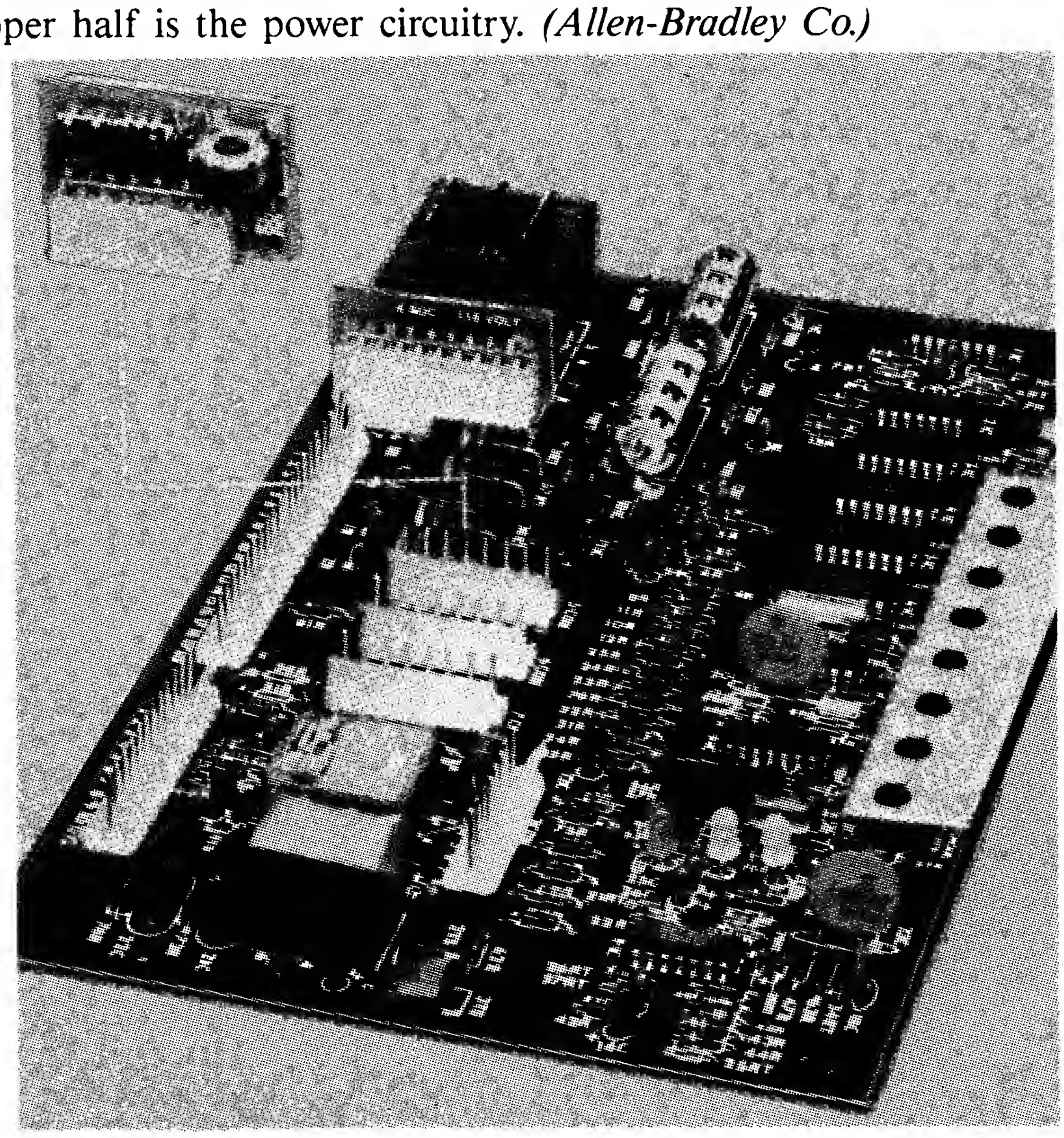


Fig. 7-96. A regulator board and a module showing how the module plugs into the regulator board. *(Allen-Bradley Co.)*

Figures 7-95; 7-96

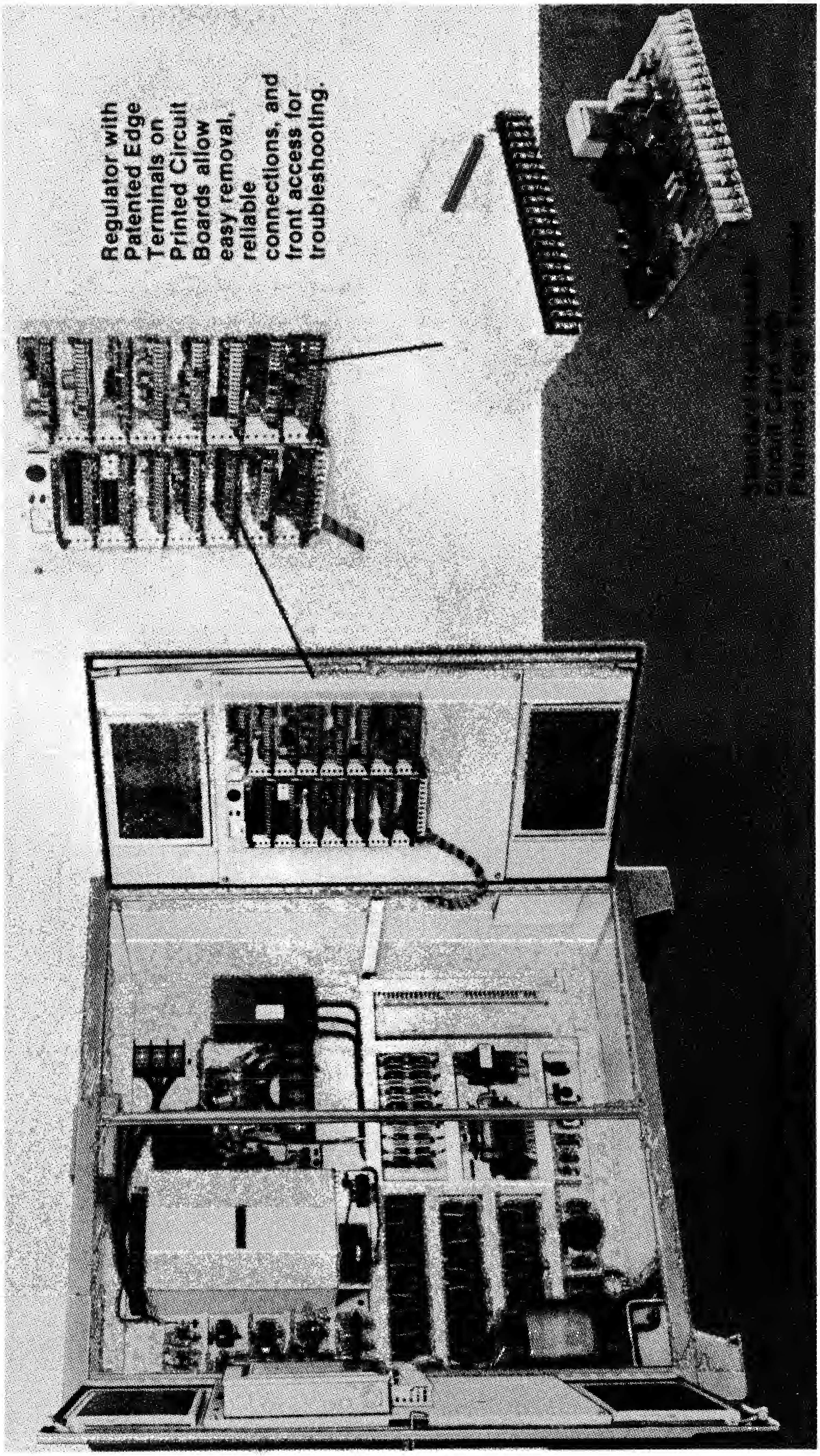


Fig. 7-97. A large, three-phase-powered, dc motor controller. *(Allen-Bradley Co.)*

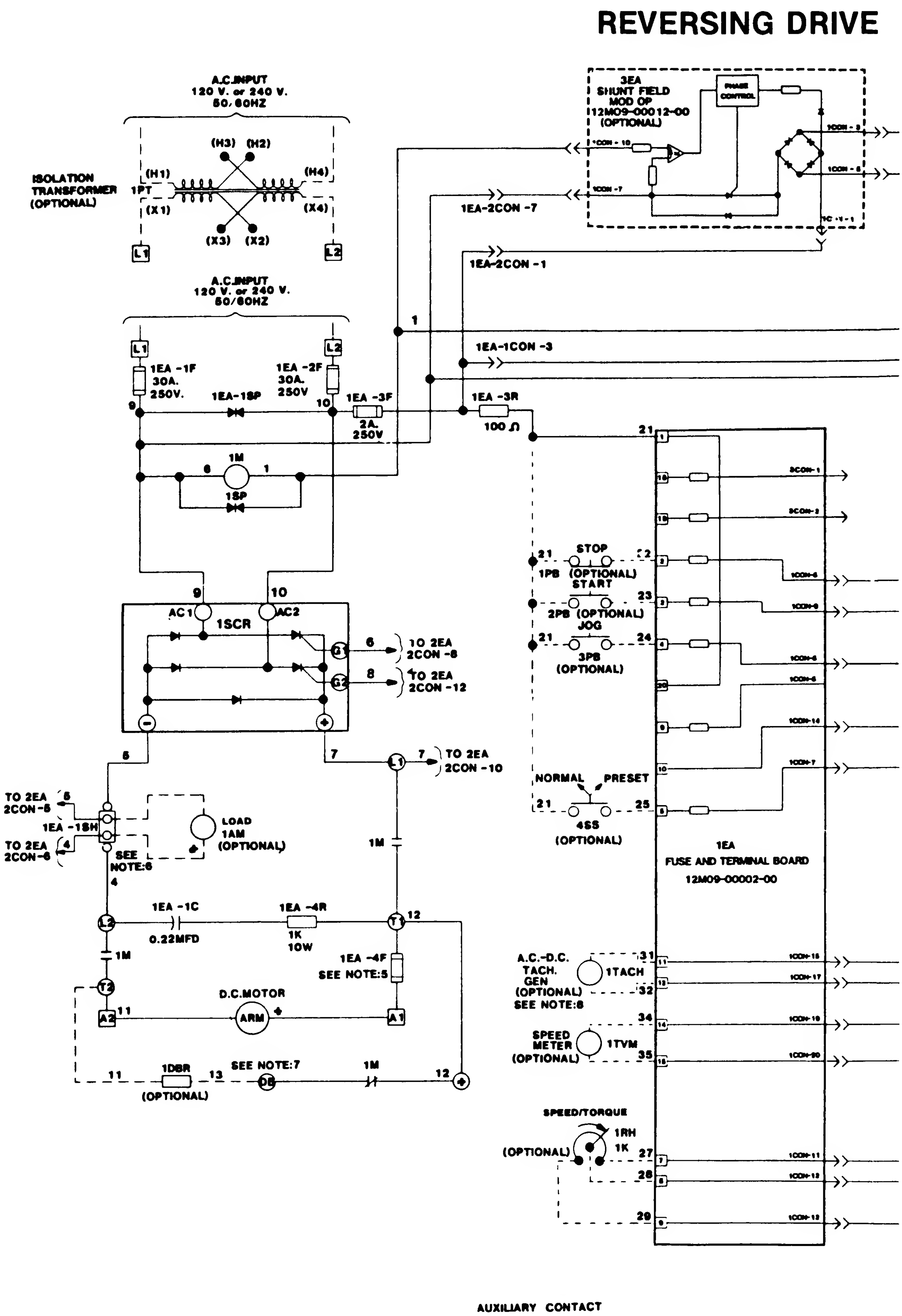
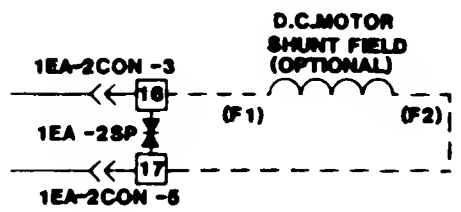


Fig. 7-98. A schematic that is included in the controller bulletin. *(Allen-Bradley Co.)*

Figure 7-98 *(con't.)*

SCHEMATIC



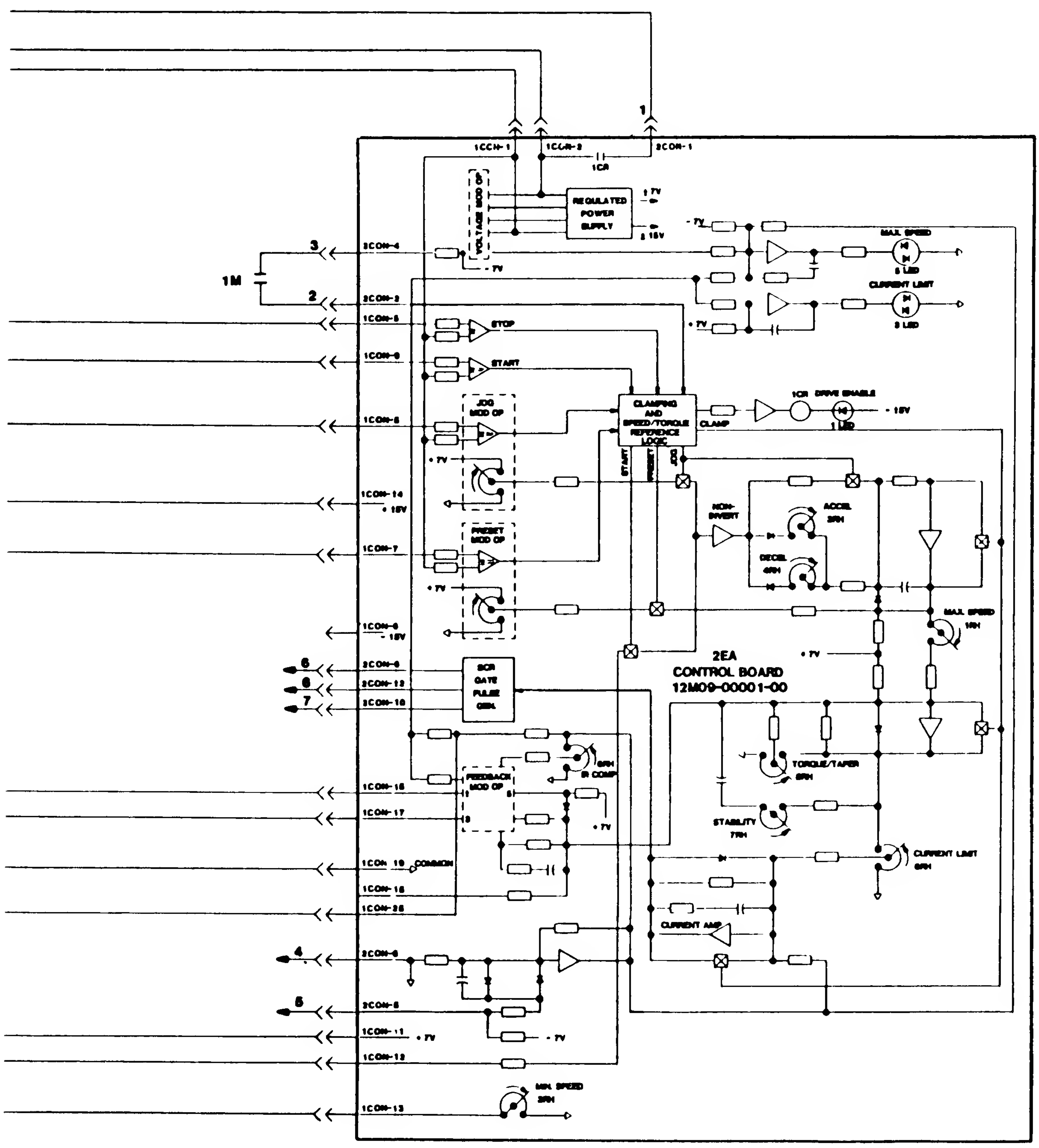


Fig. 7-98. (*continued*).
Bradley Co.)

CHAPTER 8

Universal, Shaded-pole, and Fan Motors

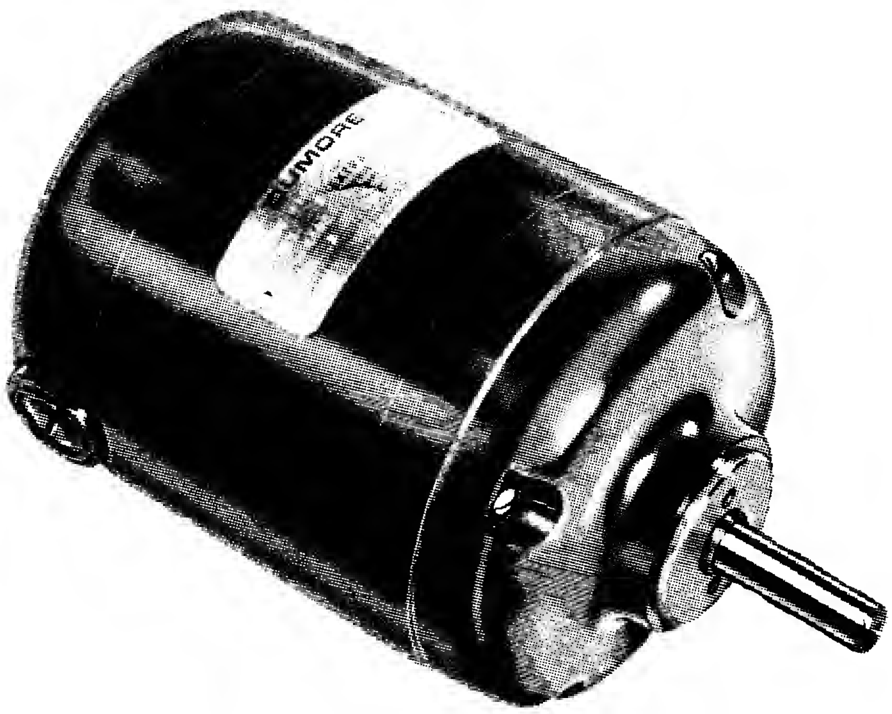


Fig. 8–1. A universal motor. *(The Dumore Co.)*

Fig. 8–2. Parts of a universal motor. *(The Dumore Co.)*

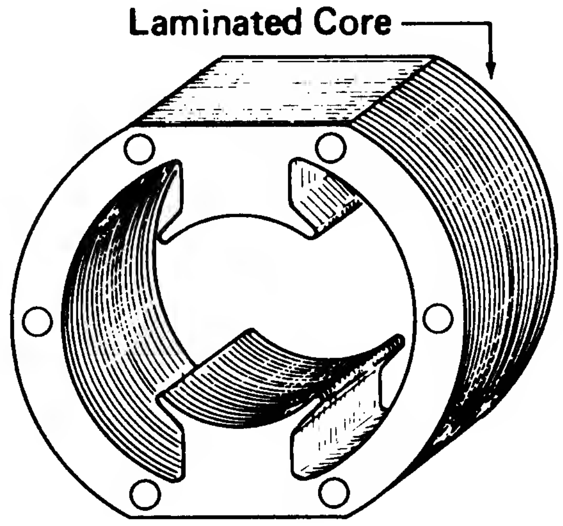
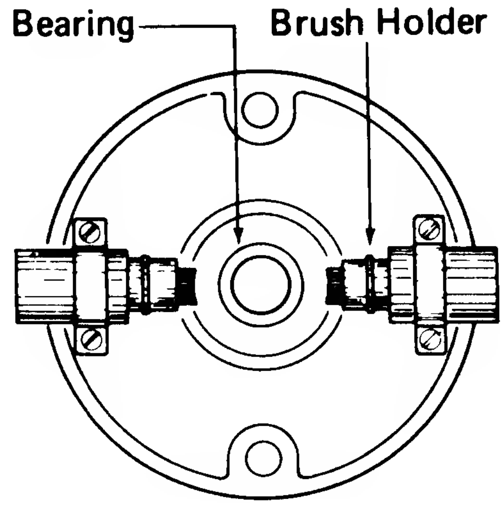


Fig. 8-3. Field core of a two-pole universal motor.

Fig. 8-4. End plate showing the brush holders and bearing.



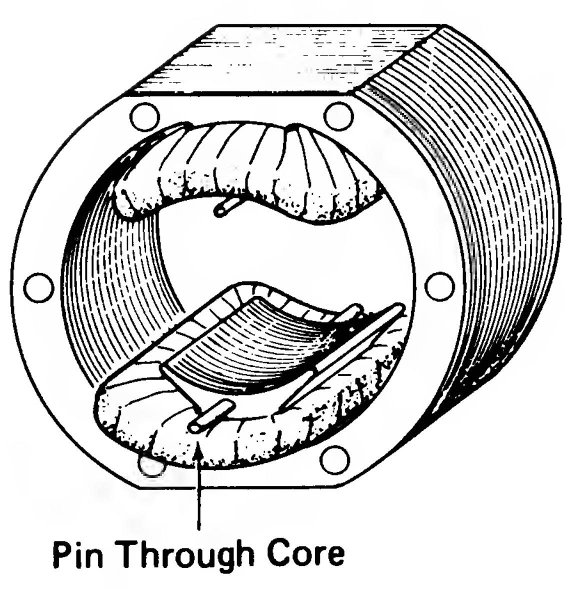
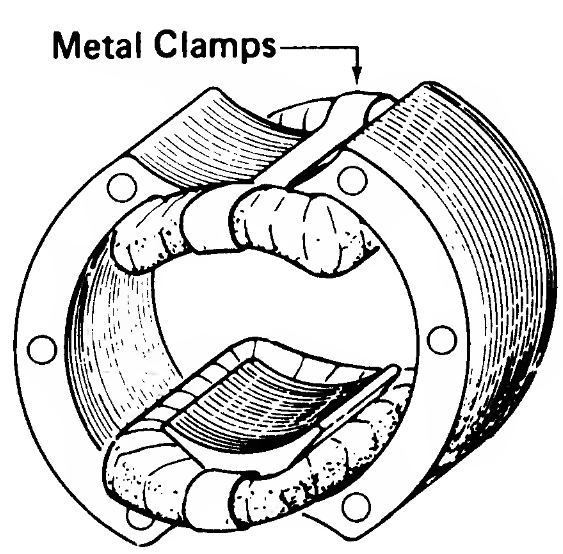


Fig. 8-5. Pins through the core hold the field coils in place.

Fig. 8-6. Method of securing coils to the core by using metal clamps.



Figures **8-3; 8-4; 8-5; 8-6**

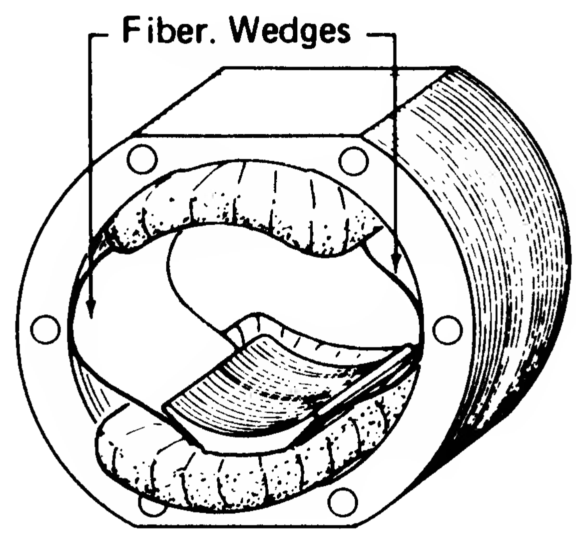


Fig. 8–7. Using fiber wedges to secure field coils to the core.

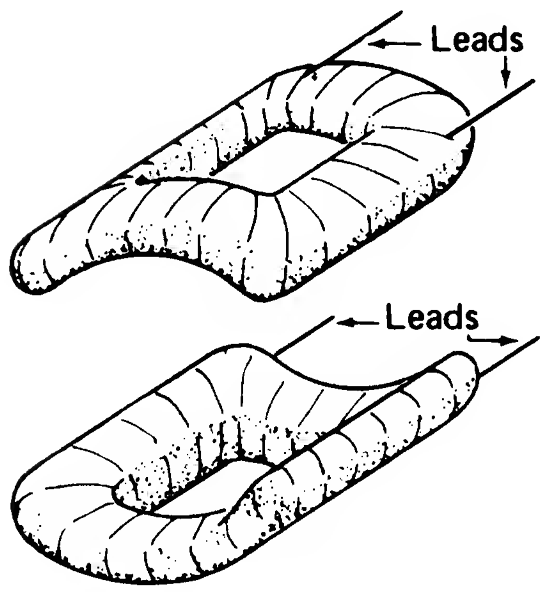


Fig. 8–8. Shape of coils after removal from the core.

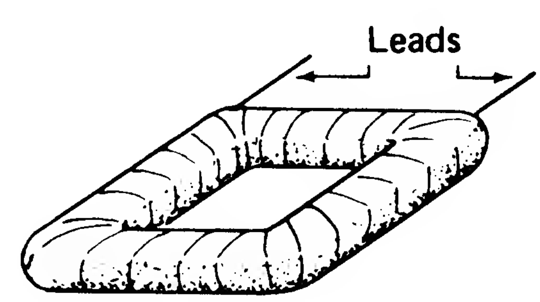


Fig. 8–9. Shape of coil after it is flattened to obtain coil dimensions.

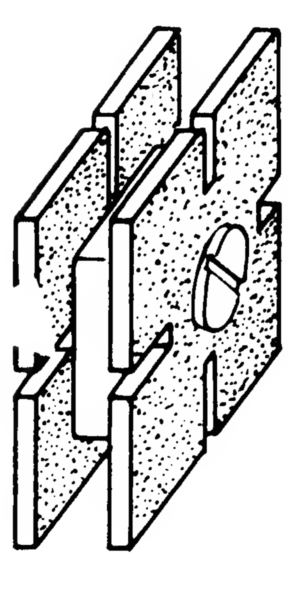


Fig. 8–10. Form for winding field coils.

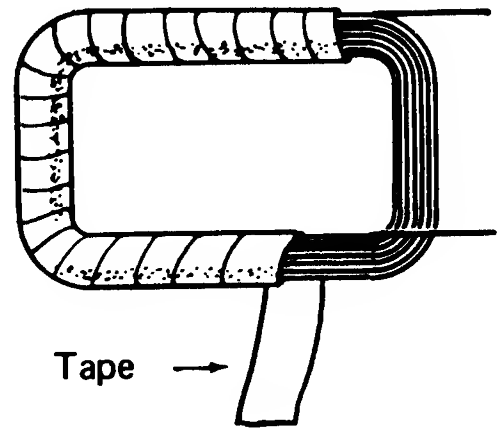


Fig. 8–11. Taping a field coil.

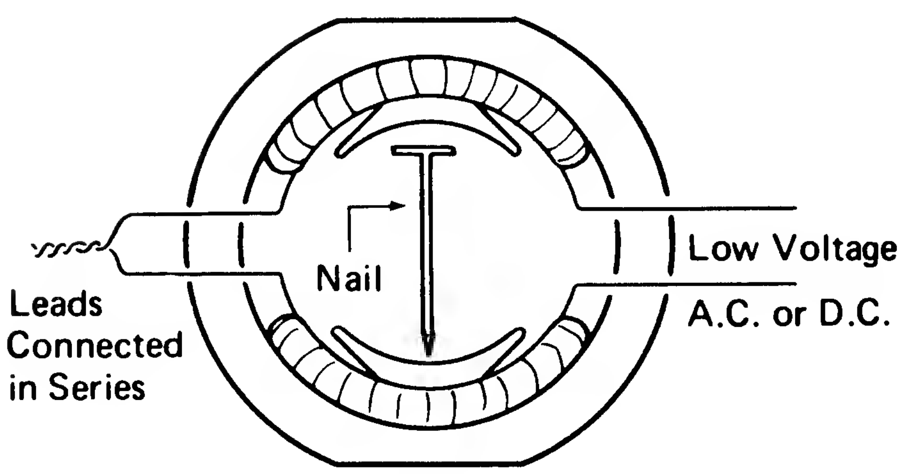


Fig. 8–12. Testing fields for proper polarity. If the nail stands between the energized coils, their polarity is correct.

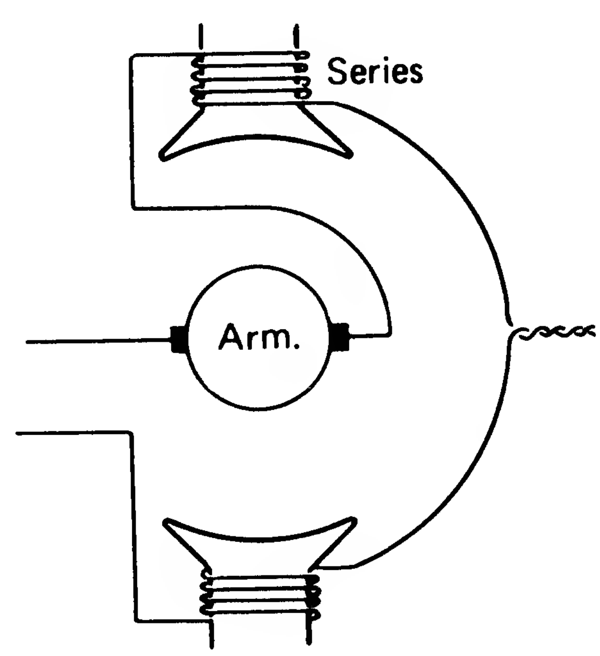


Fig. 8–13. Series connection of a universal motor.

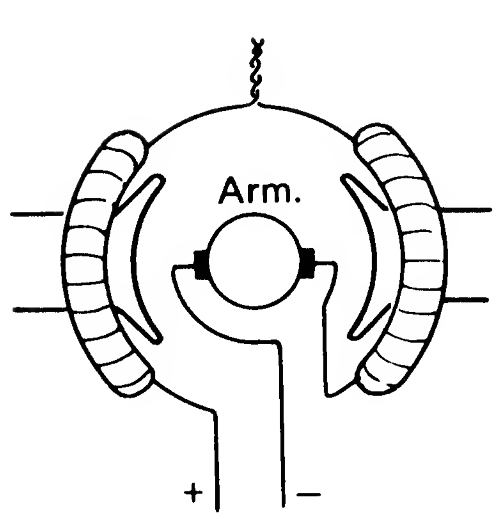


Fig. 8–14. Series connection showing taped field coils.

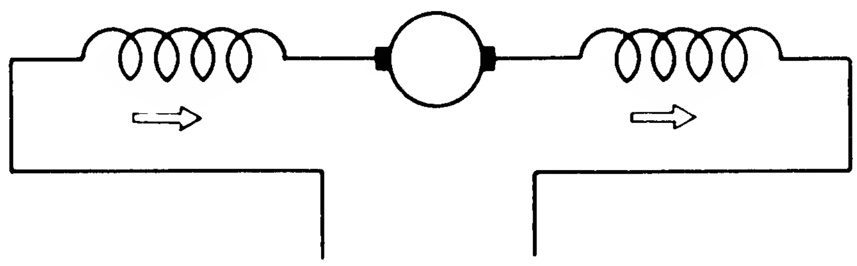


Fig. 8–15. Schematic connection of a universal motor. Note the armature is connected between the field poles.

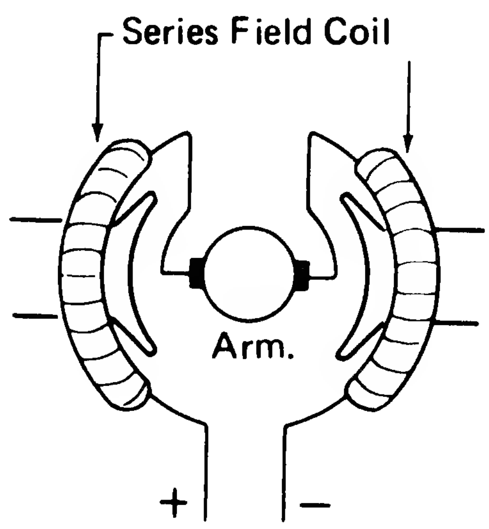
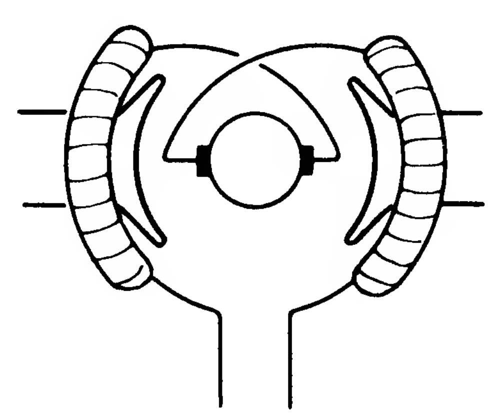


Fig. 8–16. Motor connection for clockwise rotation.

Fig. 8–17. Motor of **Fig. 8–16** connected for counterclockwise rotation by interchanging armature connections.



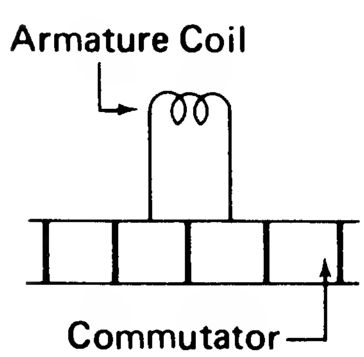
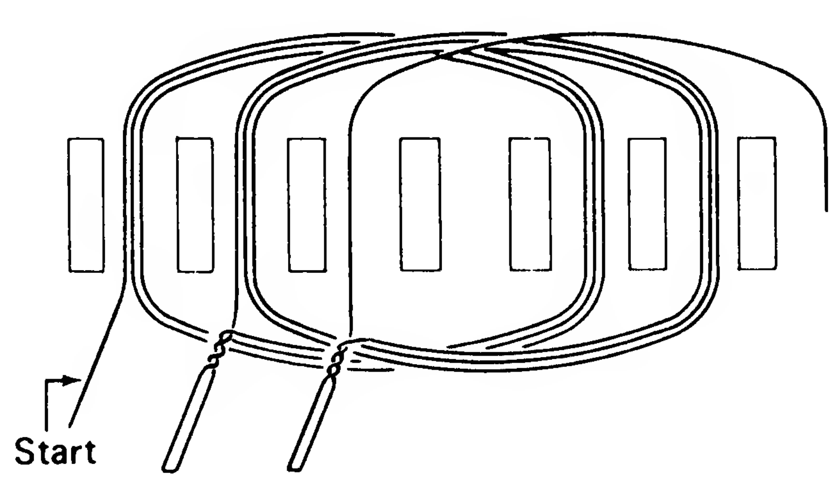


Fig. 8–18. In a lap-wound armature, each coil connects between adjacent bars.

Fig. 8–19. A loop winding showing loops at the end of each coil.



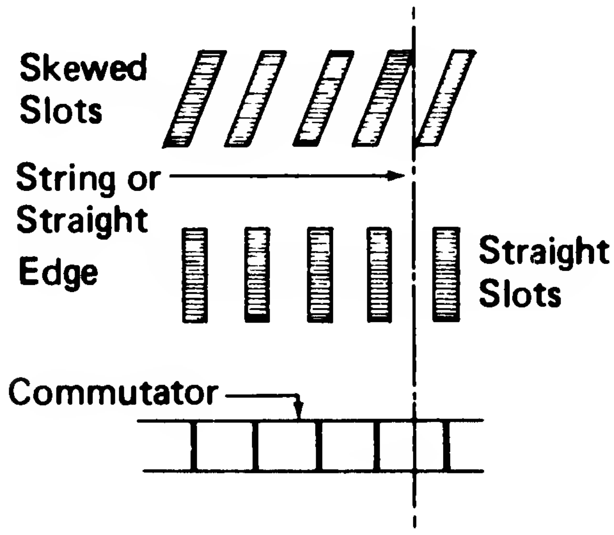
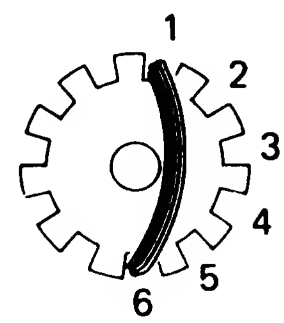


Fig. 8-20. Lining out the center of slots to the commutator to determine lead throw.

Fig. 8-21. View of the armature from the end opposite the commutator to determine the coil pitch.



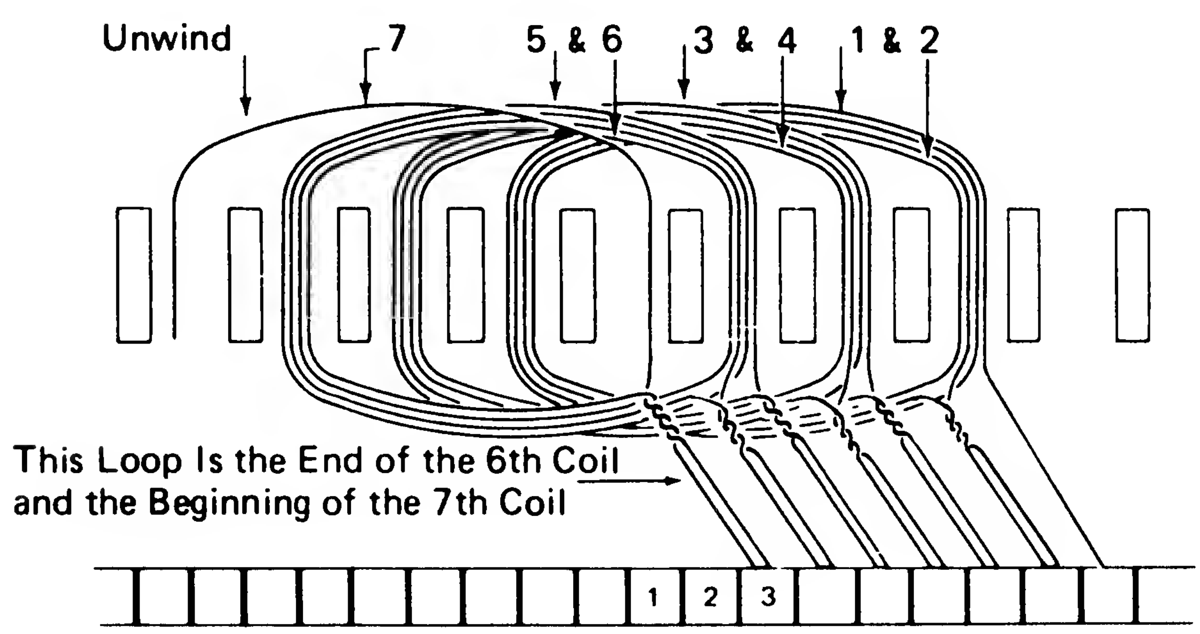


Fig. 8-22. Coils being unwound turn by turn to record the position of the leads to the commutator bars.

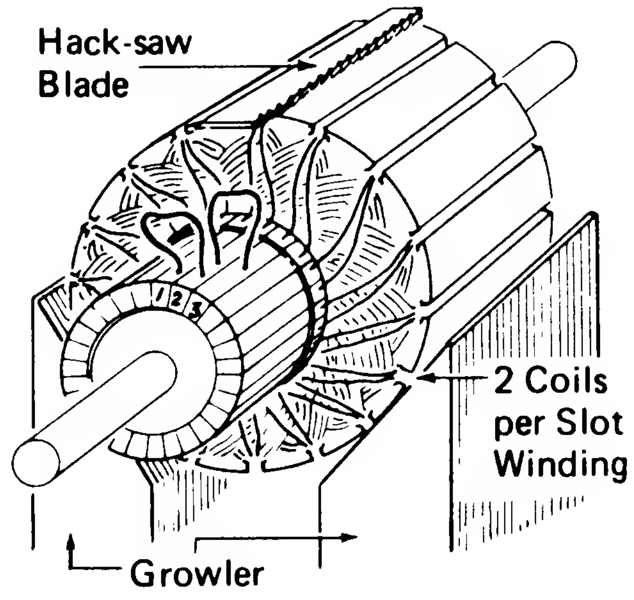


Fig. 8-23. The hacksaw blade vibrates if bars 1 and 2 and 2 and 3 are shorted while the armature is in the growler. This determines the lead throw of the coils.

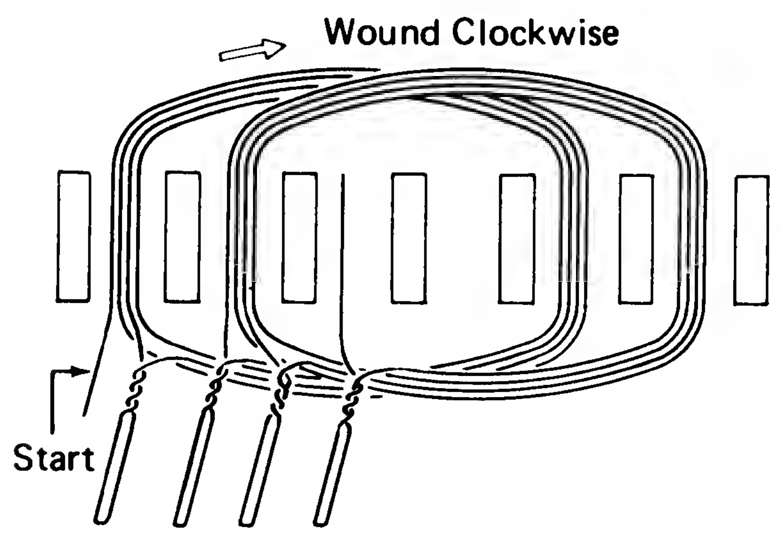


Fig. 8-24. Coils in an armature wound in a clockwise direction.

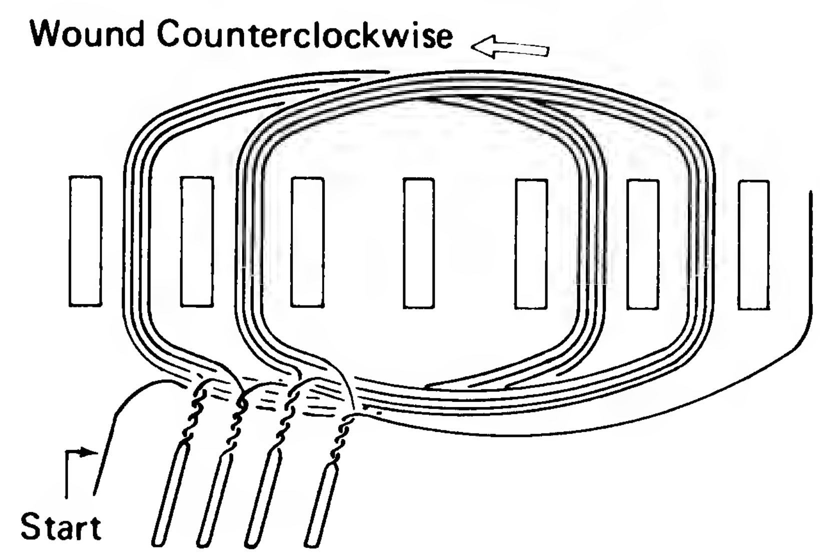


Fig. 8-25. Coils wound in a counter-clockwise direction.

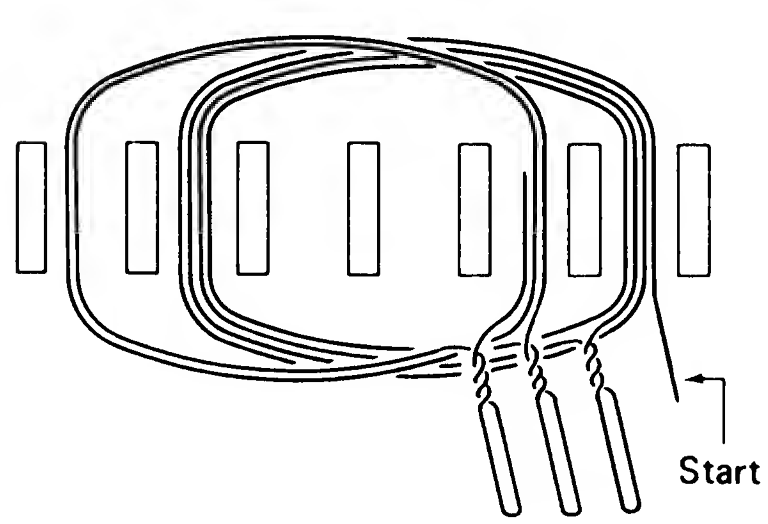


Fig. 8-26. Loops for making connections to commutator shown on the right side of the coils.

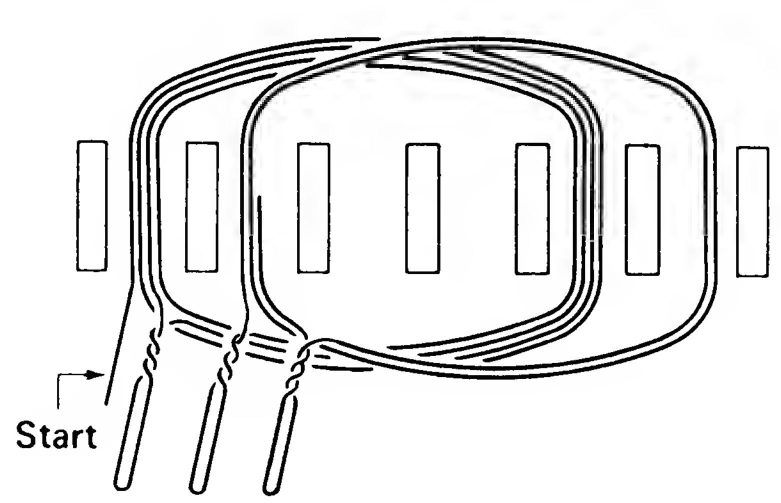


Fig. 8-27. Loops shown on the left side of each coil.

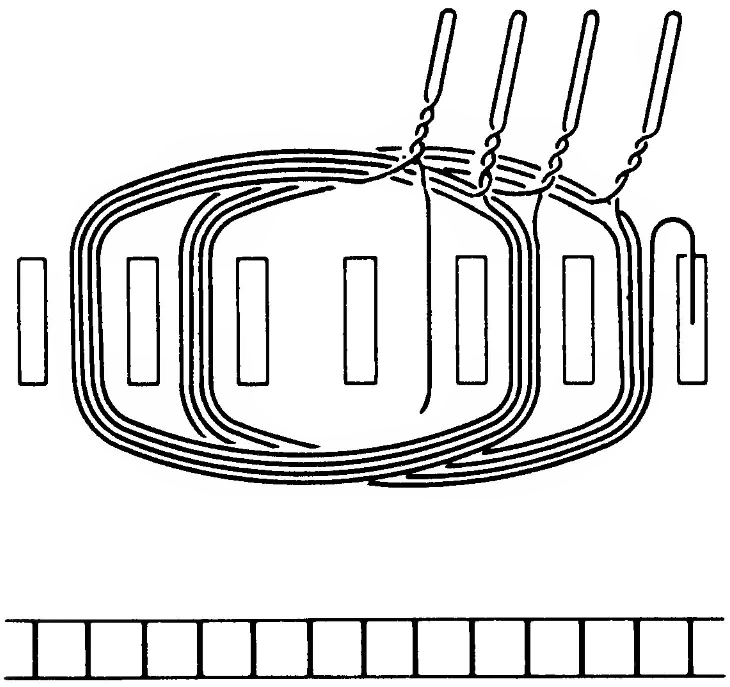


Fig. 8–28. In some armatures the loops are made at the rear of the slots and brought back through the slots to the commutator.

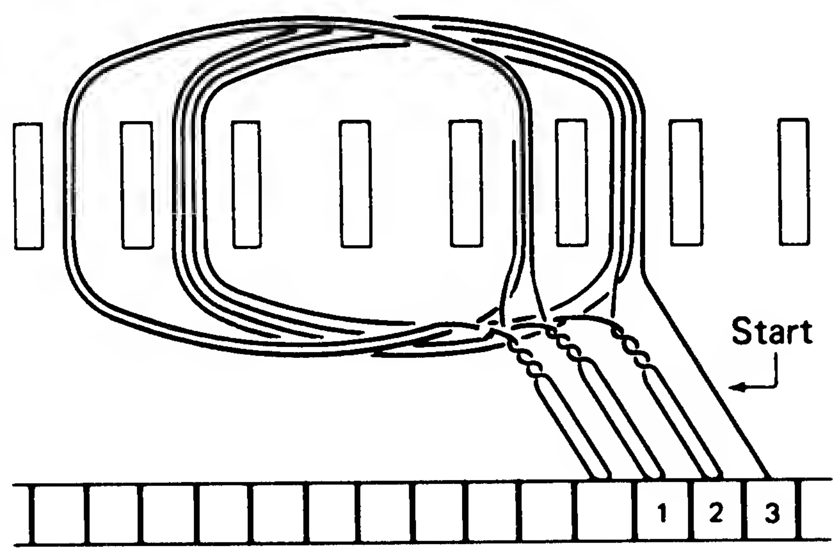


Fig. 8–29. Leads connected several bars to the right of each coil for clockwise rotation.

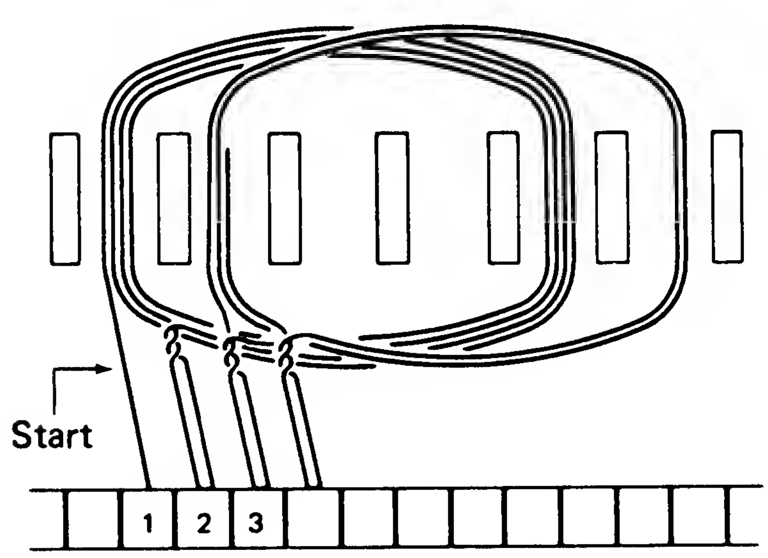


Fig. 8–30. Leads connected to the right of each coil for clockwise rotation.

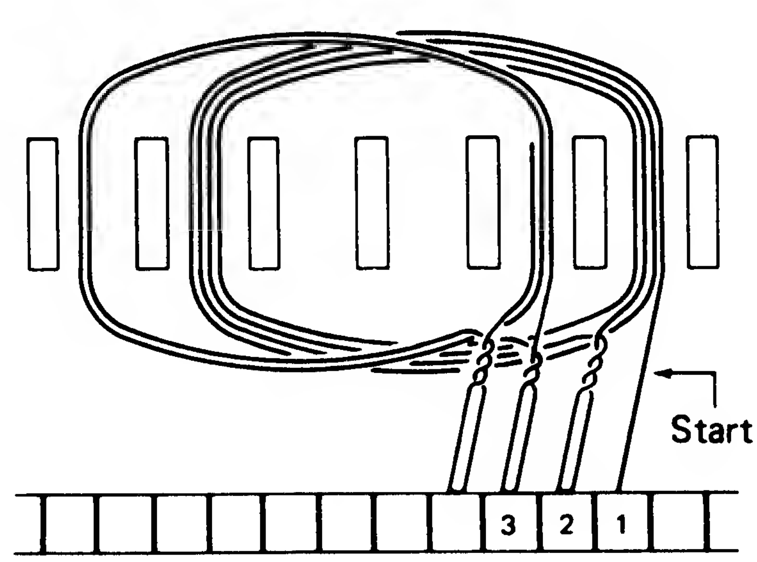


Fig. 8–31. Leads connected several bars to the left for counterclockwise rotation.

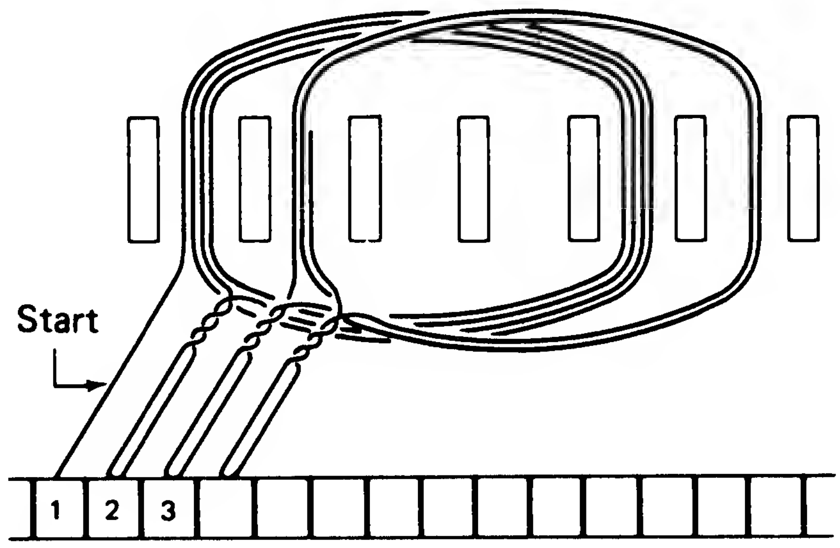


Fig. 8-32. Leads connected to the left of each coil for counterclockwise rotation.

Fig. 8-33. Parts of a distributed-field universal motor.

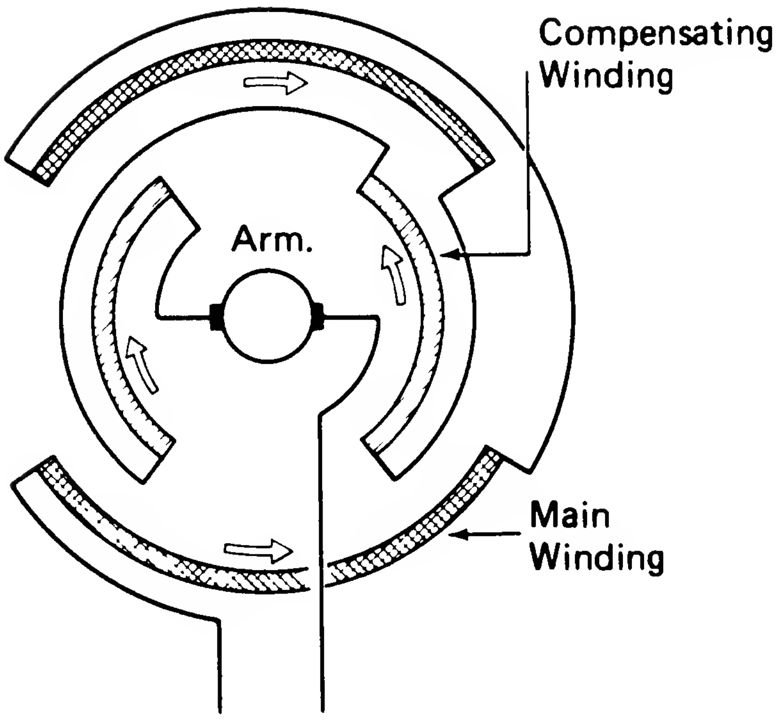


Fig. 8-34. Connections of a compensated universal motor. Note that the compensating winding is located 90 electrical degrees from the main winding and connected in series with the armature and main winding.

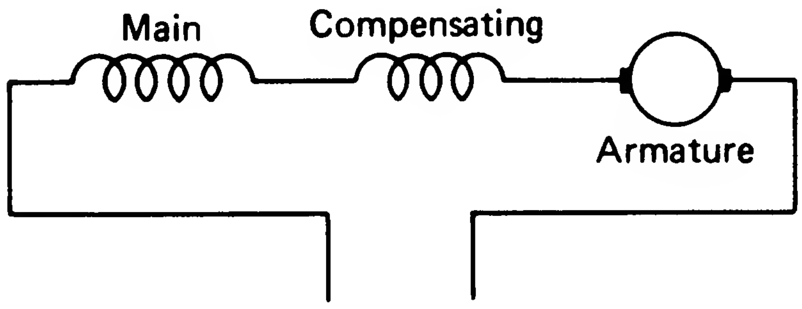


Fig. 8-35. Schematic diagram of a compensated universal motor.

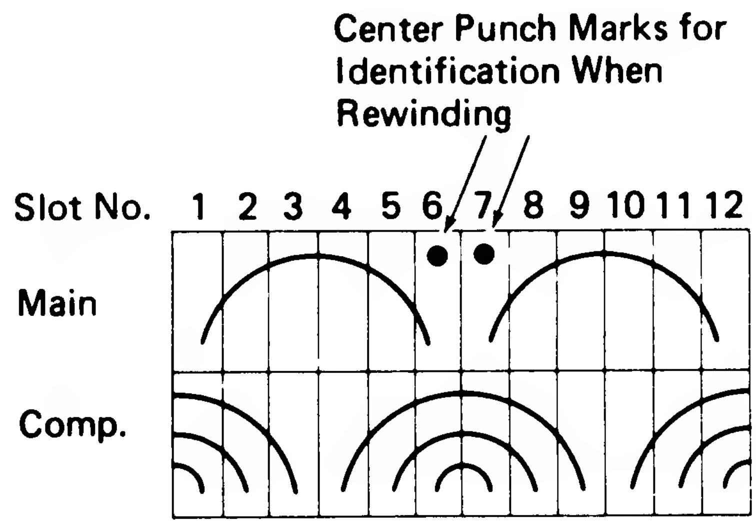


Fig. 8-36. Recording the windings of a twelve-slot, two-pole, compensated universal motor. Note the center-punch marks in the slots to locate the windings in the proper slots.

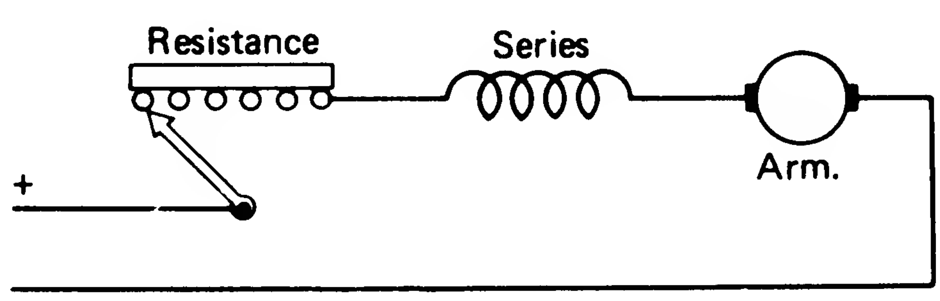


Fig. 8-37. Speed of a small universal motor controlled by connecting a variable resistor in series with the motor.

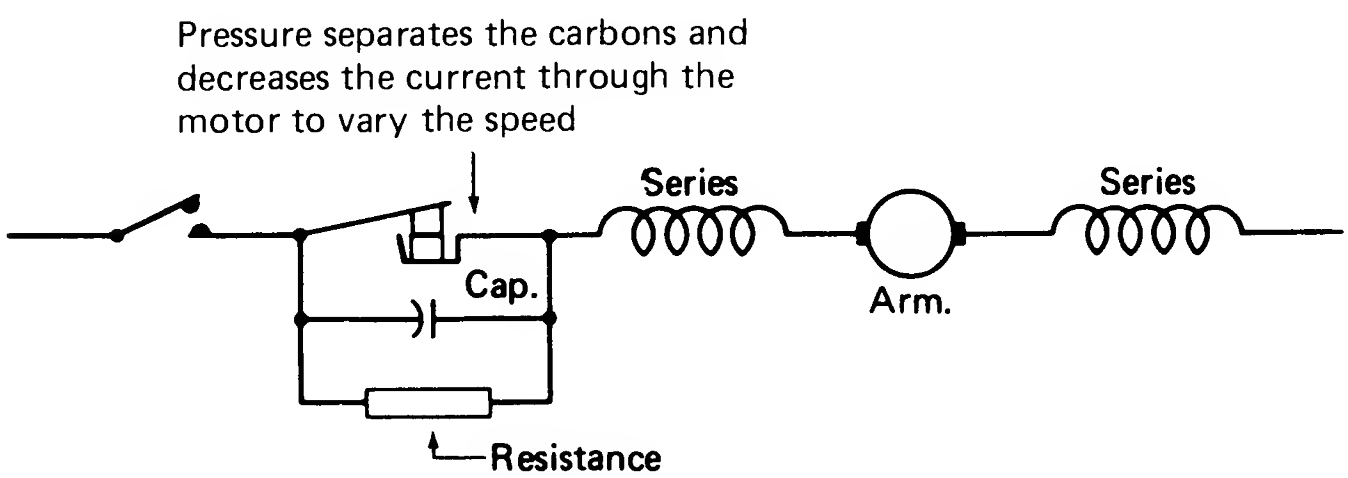


Fig. 8-38. Speed control of a universal motor by a variation in contact resistance between two carbon blocks.

Figures **8**-35; **8**-36; **8**-37; **8**-38

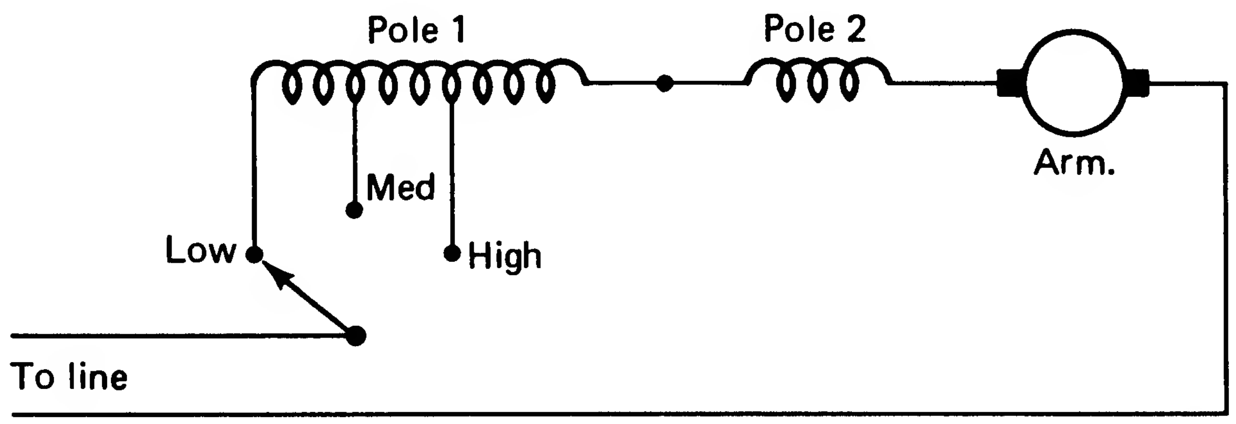


Fig. 8-39. Three speeds are obtained by tapping one field pole.

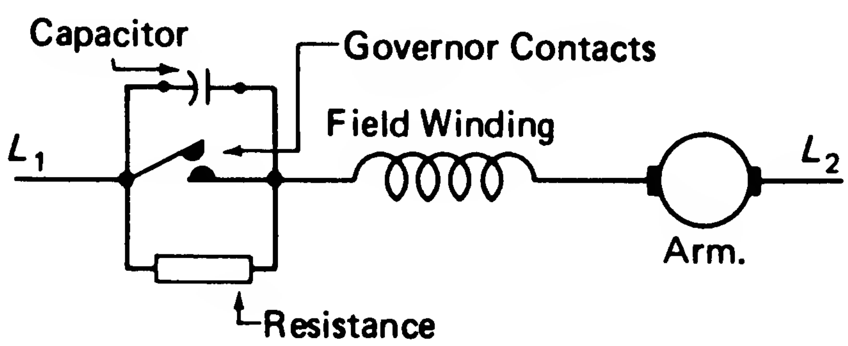
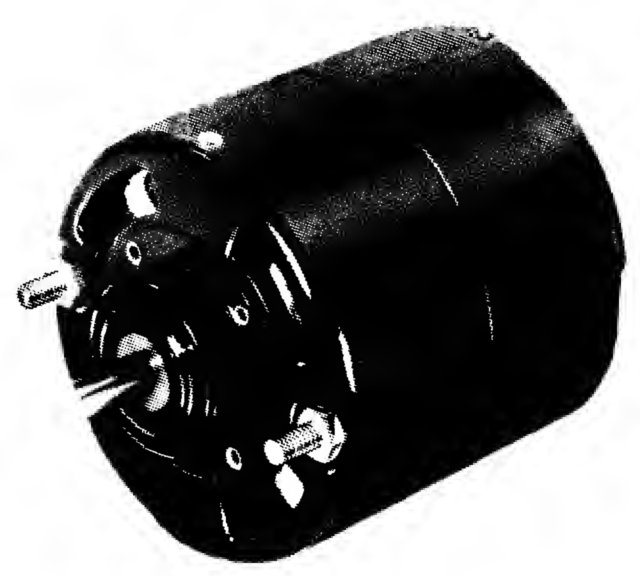


Fig. 8-40. Speed control of a universal motor by means of a centrifugal governor.

Fig. 8-41. A shaded-pole motor. *(Emerson Elec. Mfg. Co.)*



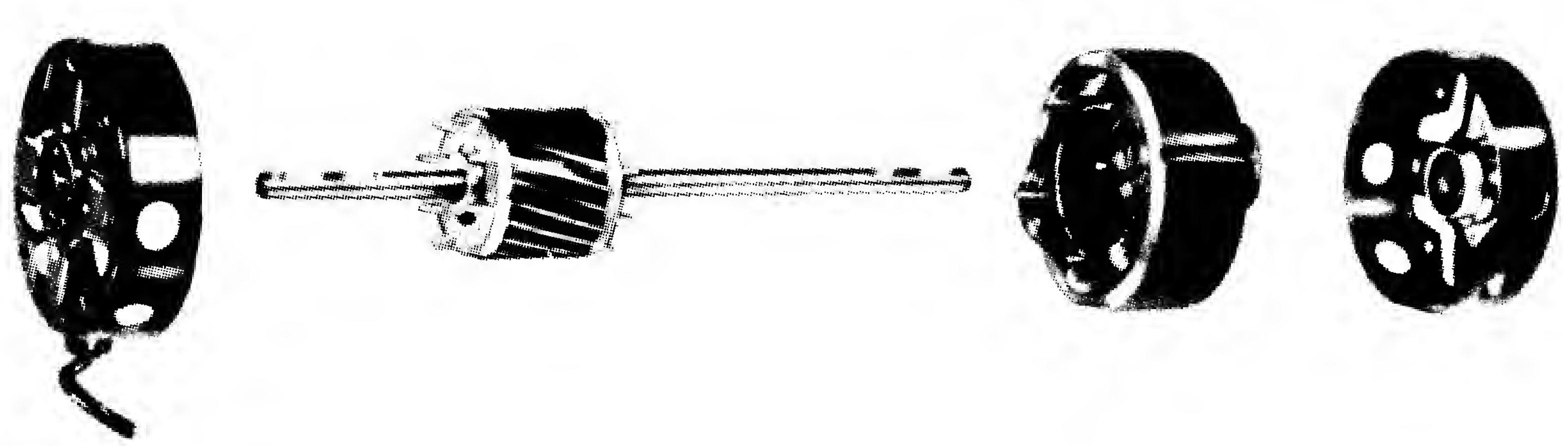


Fig. 8-42. Construction of the field and armature of a shaded-pole motor.

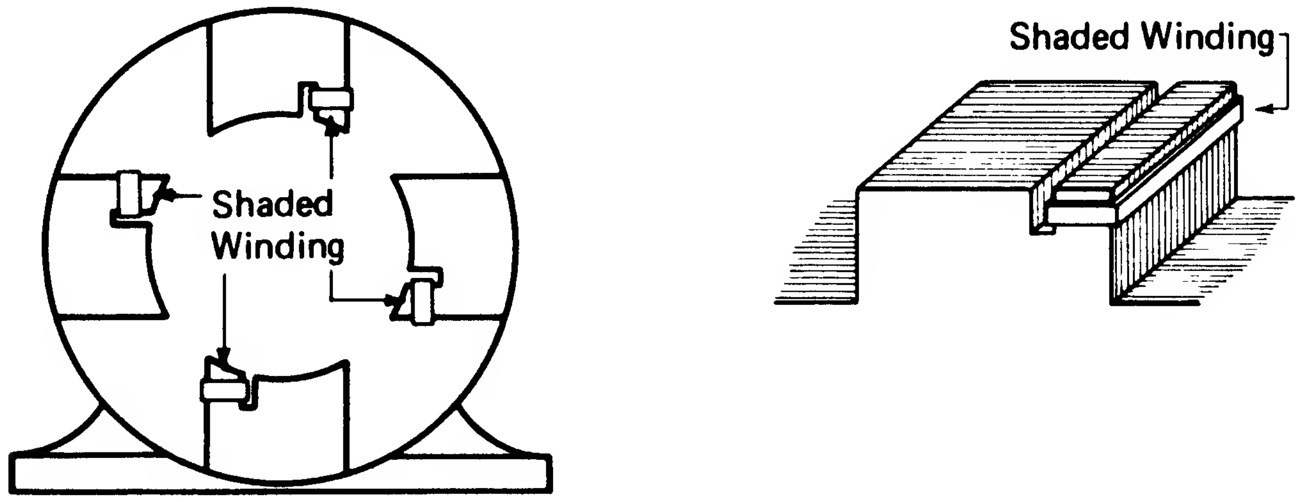


Fig. 8-43. A four-pole, shaded-pole motor showing the field poles and shading windings.

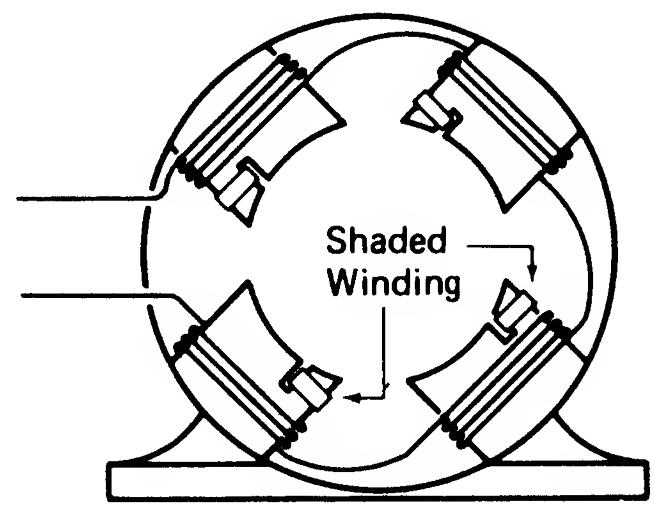


Fig. 8-44. A four-pole, shaded-pole motor with the field poles connected in series for alternate polarity.

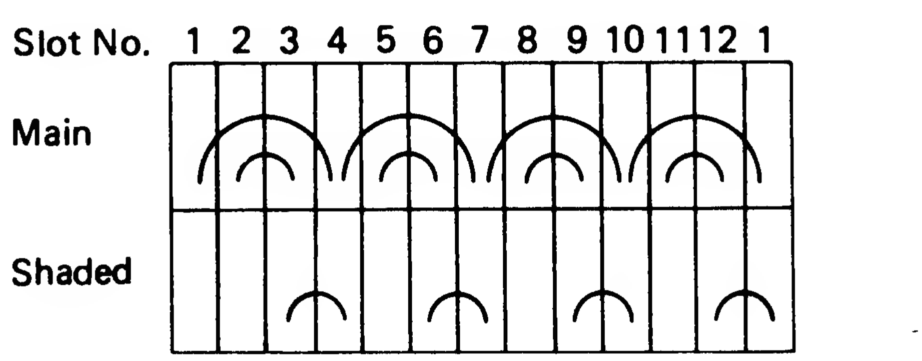


Fig. 8-45. Recording the windings of a four-pole, 12-slot, distributed shaded-pole motor.

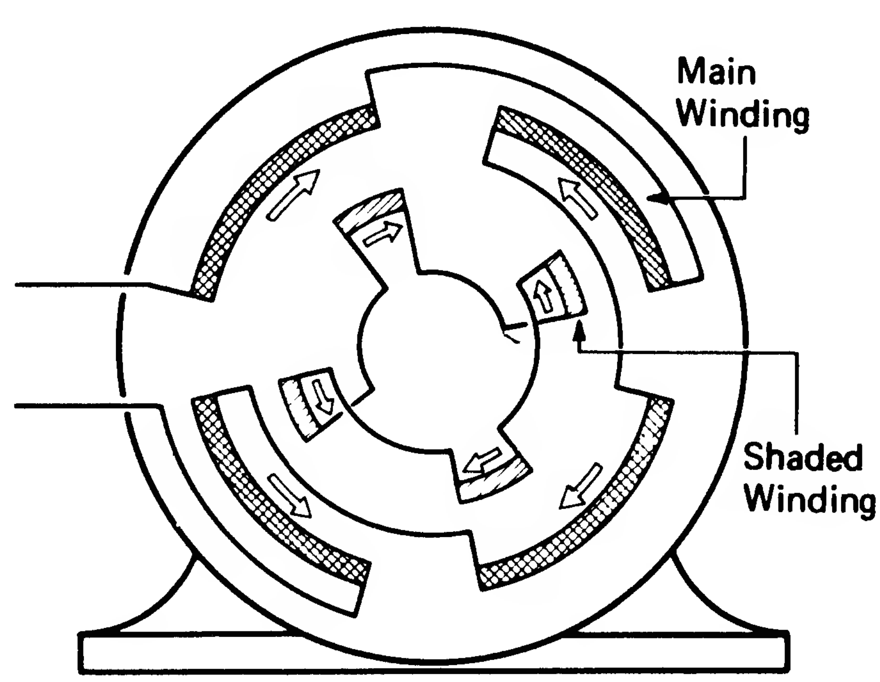


Fig. 8-46. Connection diagram of a four-pole, distributed shaded-pole winding.

Figures 8-43; 8-44; 8-45; 8-46

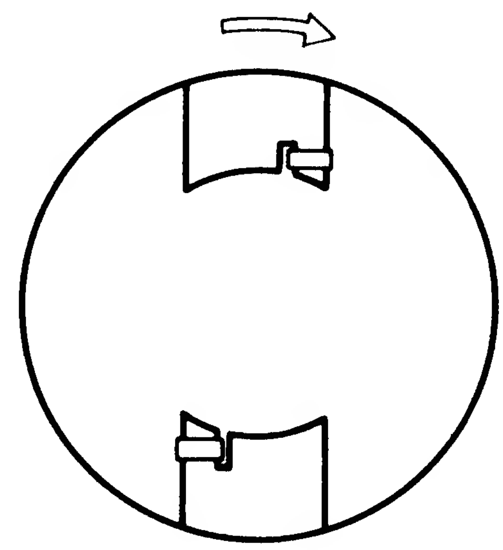


Fig. 8–47. Position of the poles and shading coils before the stator is reversed.

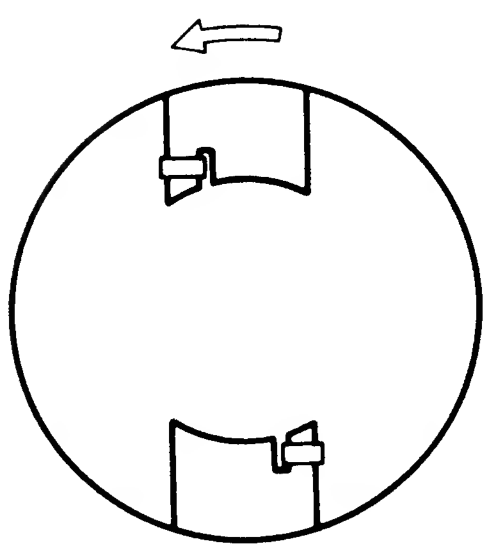


Fig. 8–48. Position of the poles after the stator is reversed end for end. Compare with **Fig. 8–47.**

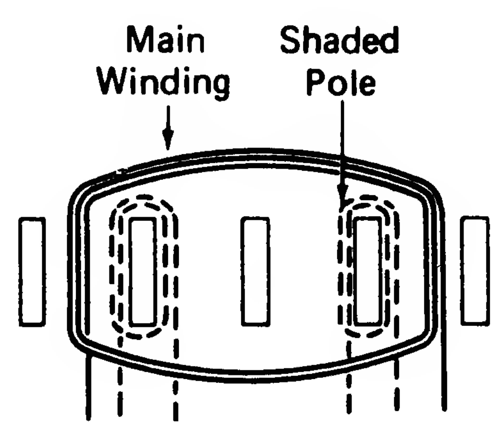


Fig. 8–49. One pole of a 12-slot, reversible shaded-pole motor. Note the two shading coils.

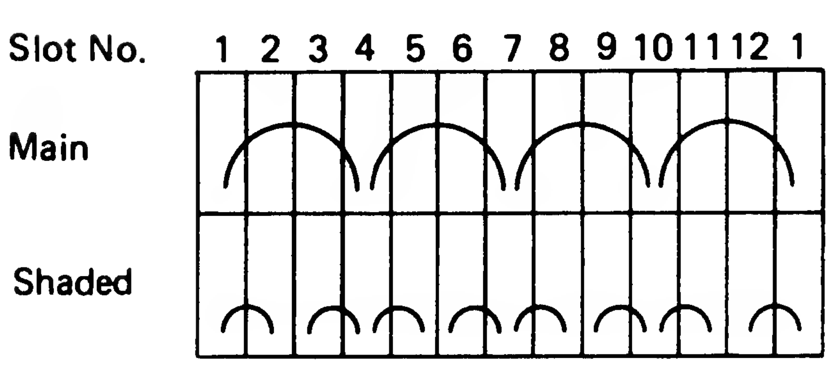


Fig. 8–50. Coil layout of a reversible shaded-pole motor.

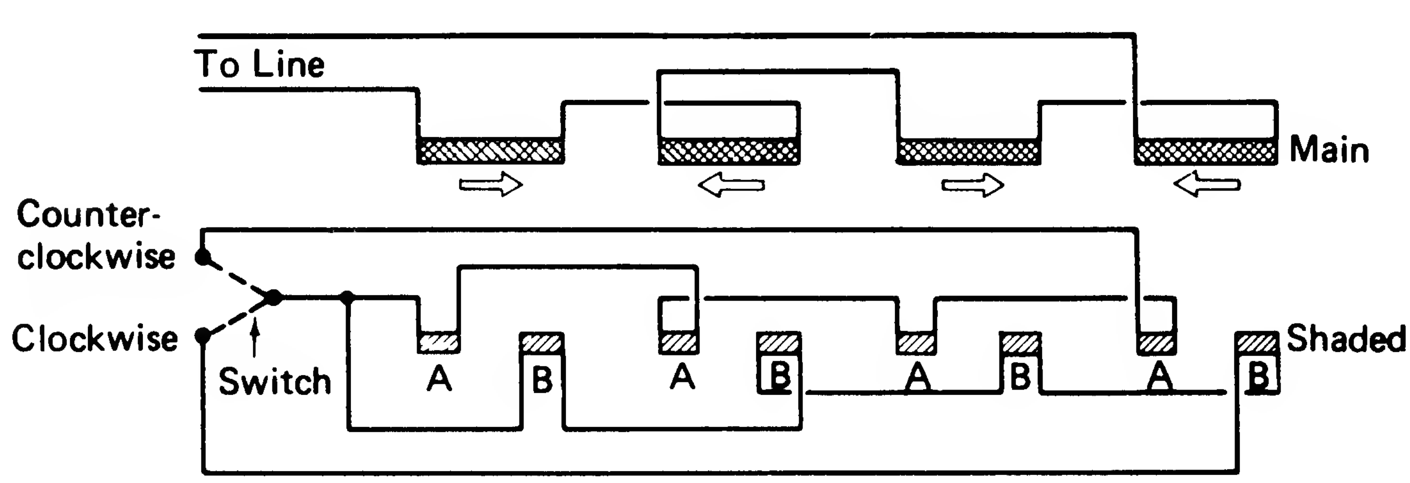


Fig. 8–51. Wiring diagram of a reversible shaded-pole motor. To reverse a shaded-pole motor, one series of shading coils is opened and the other series closed.

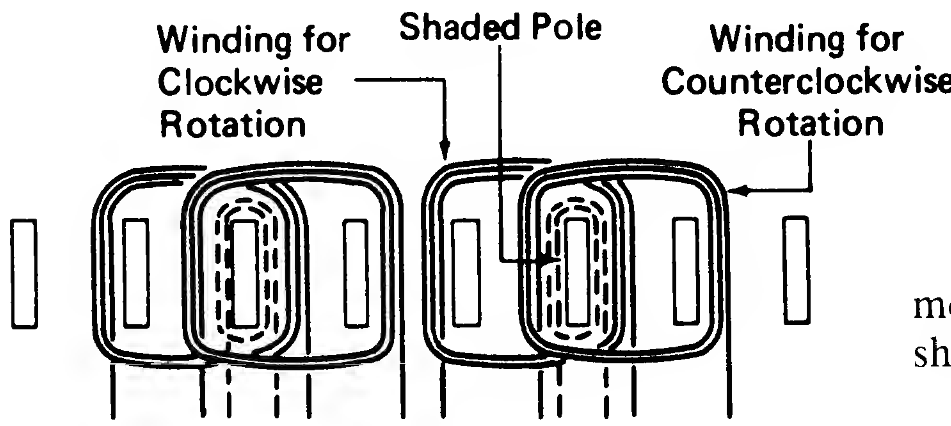


Fig. 8–52. Reversible shaded-pole motor with two main poles for each shaded coil.

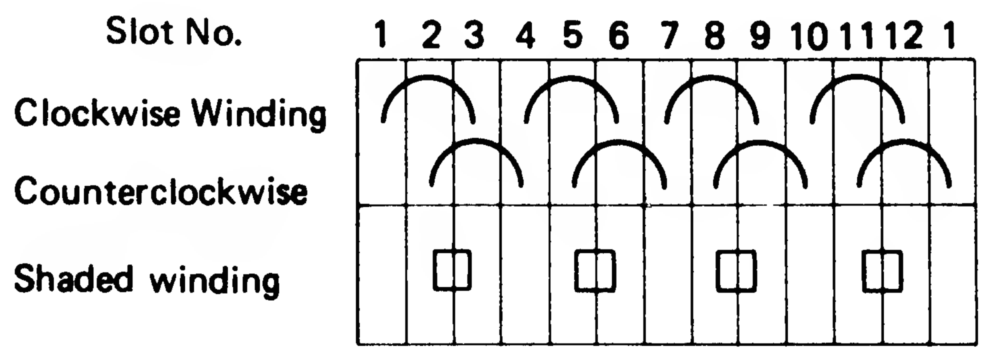


Fig. 8–53. Method of recording the layout of the coils of a 12-slot, four-pole, reversible shaded-pole motor having two sets of main poles.

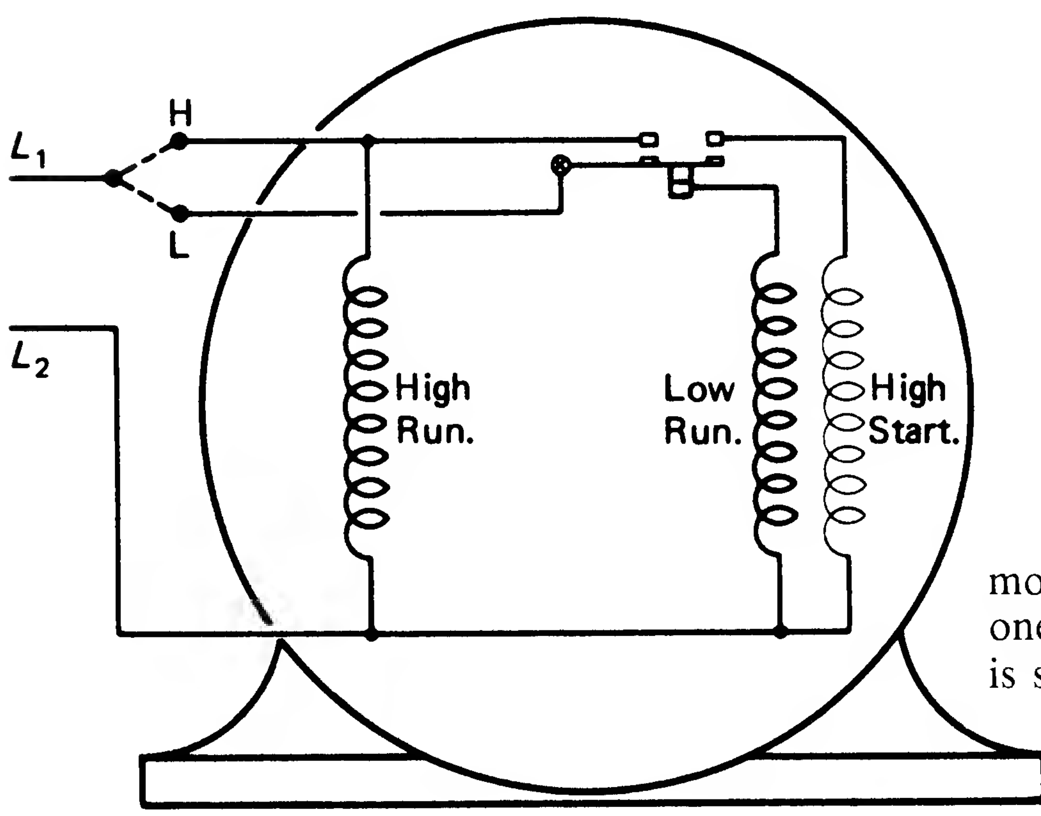


Fig. 8–54. A two-speed, split-phase motor with two running windings and one starting winding. Centrifugal switch is shown in running position.

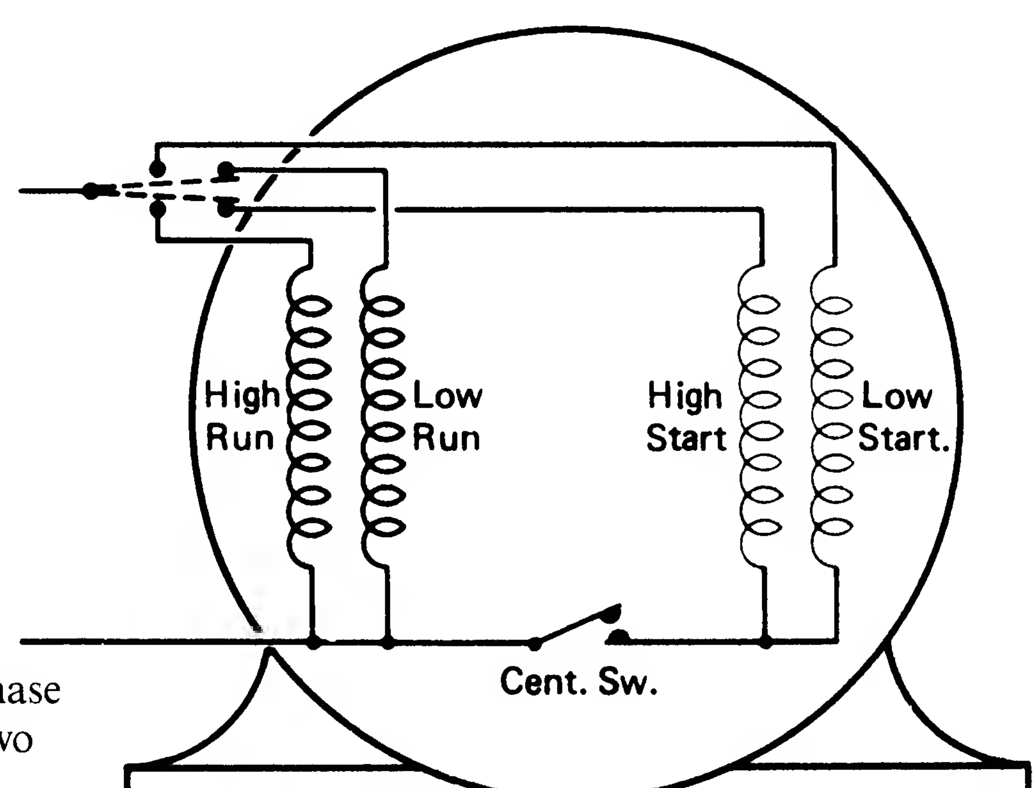


Fig. 8–55. A two-speed, split-phase fan motor with two running and two starting windings.

Figures 8–52; 8–53; 8–54; 8–55

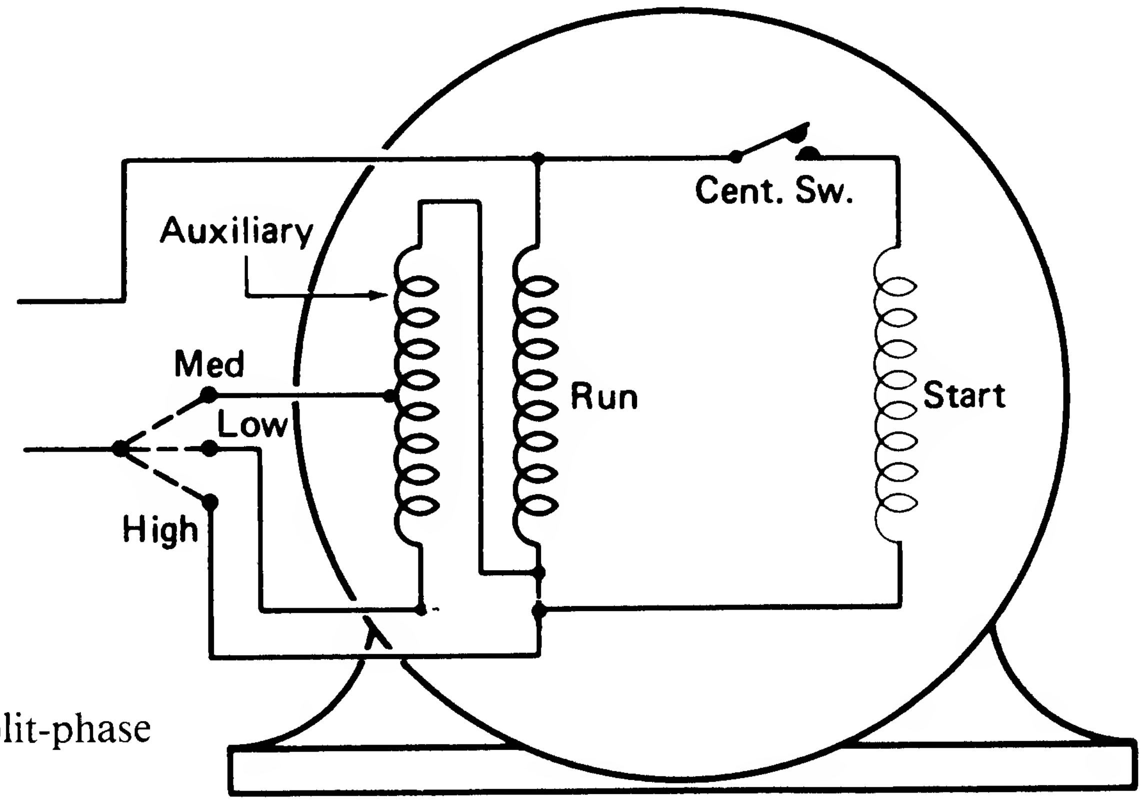


Fig. 8-56. A three-speed split-phase motor.

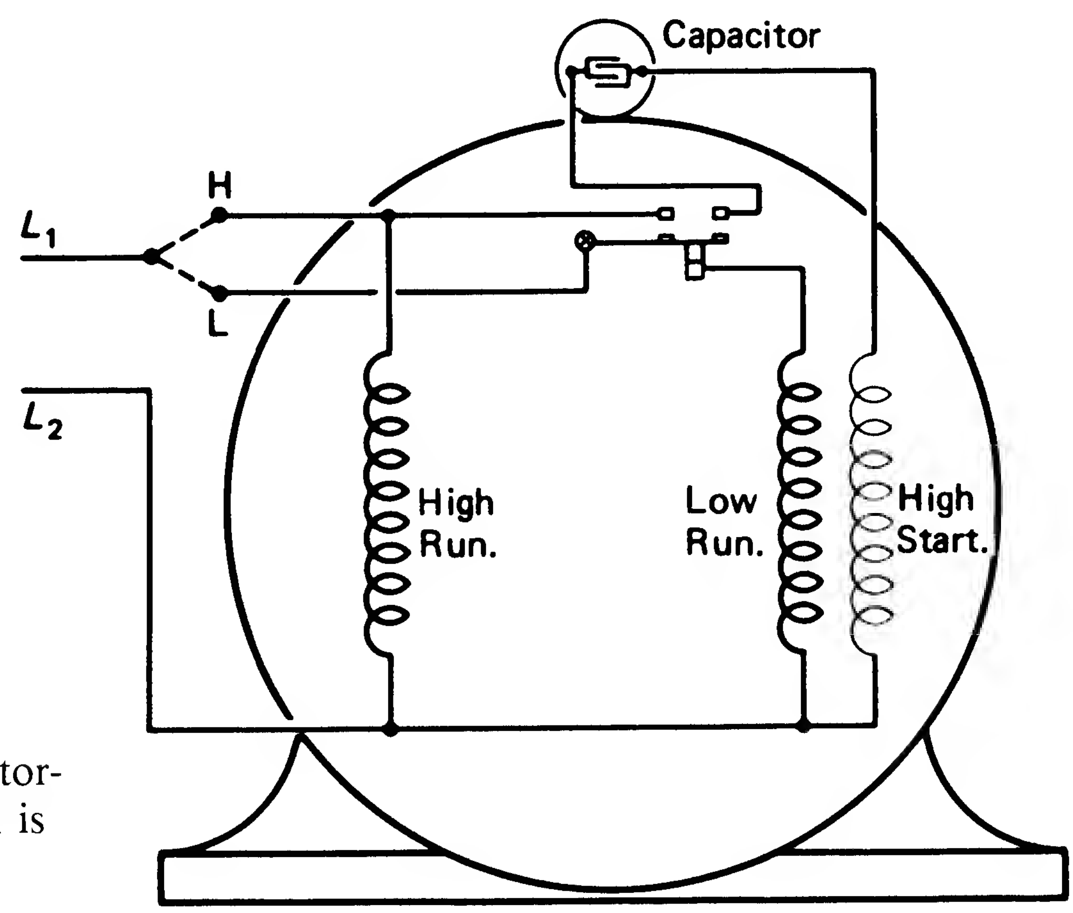


Fig. 8-57. A two-speed, capacitor-start fan motor. Centrifugal switch is shown in running position.

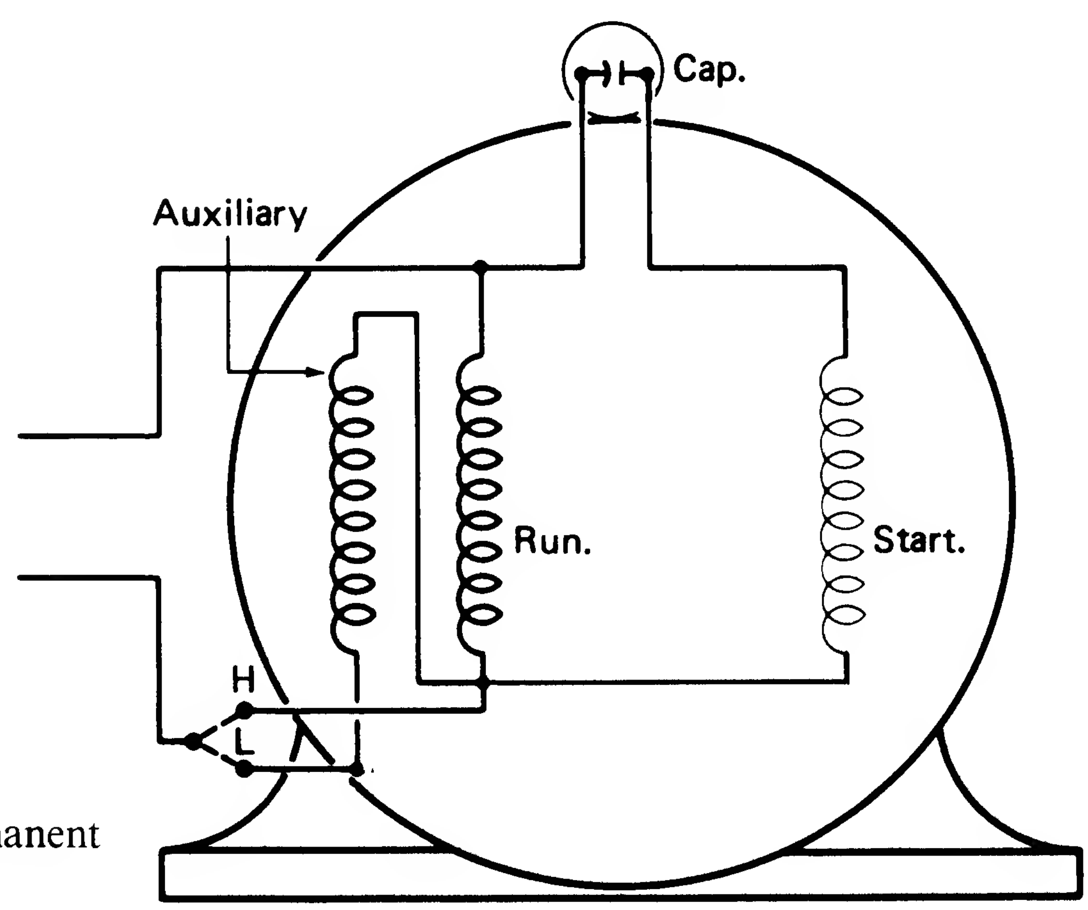


Fig. 8-58. A two-speed, (permanent split) capacitor fan motor.

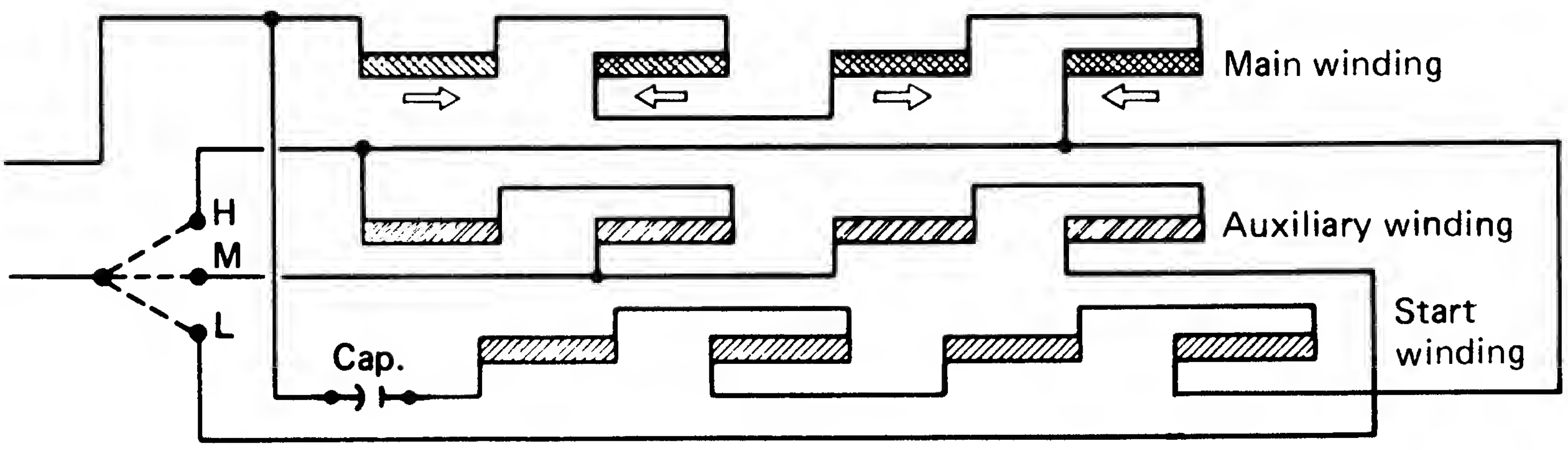


Fig. 8–59. Wiring diagram of a three-speed (permanent-split) capacitor motor.

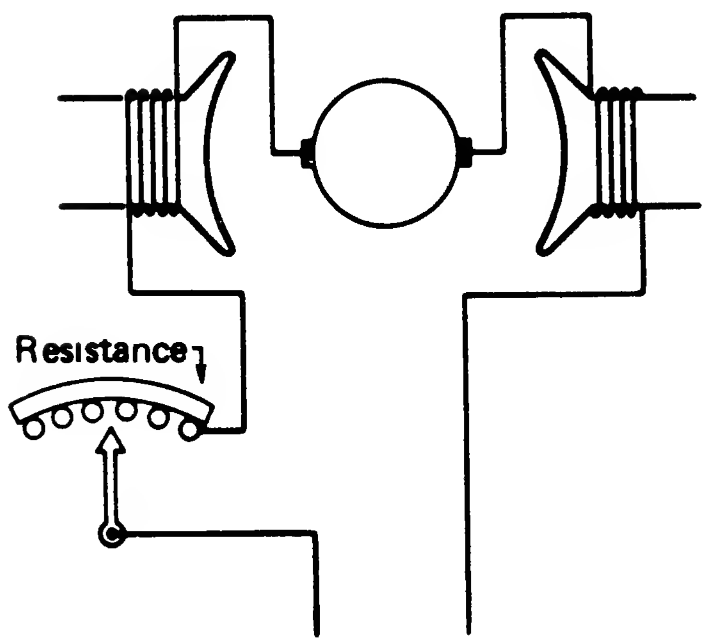


Fig. 8–60. Universal fan motor with a series resistance for speed control.

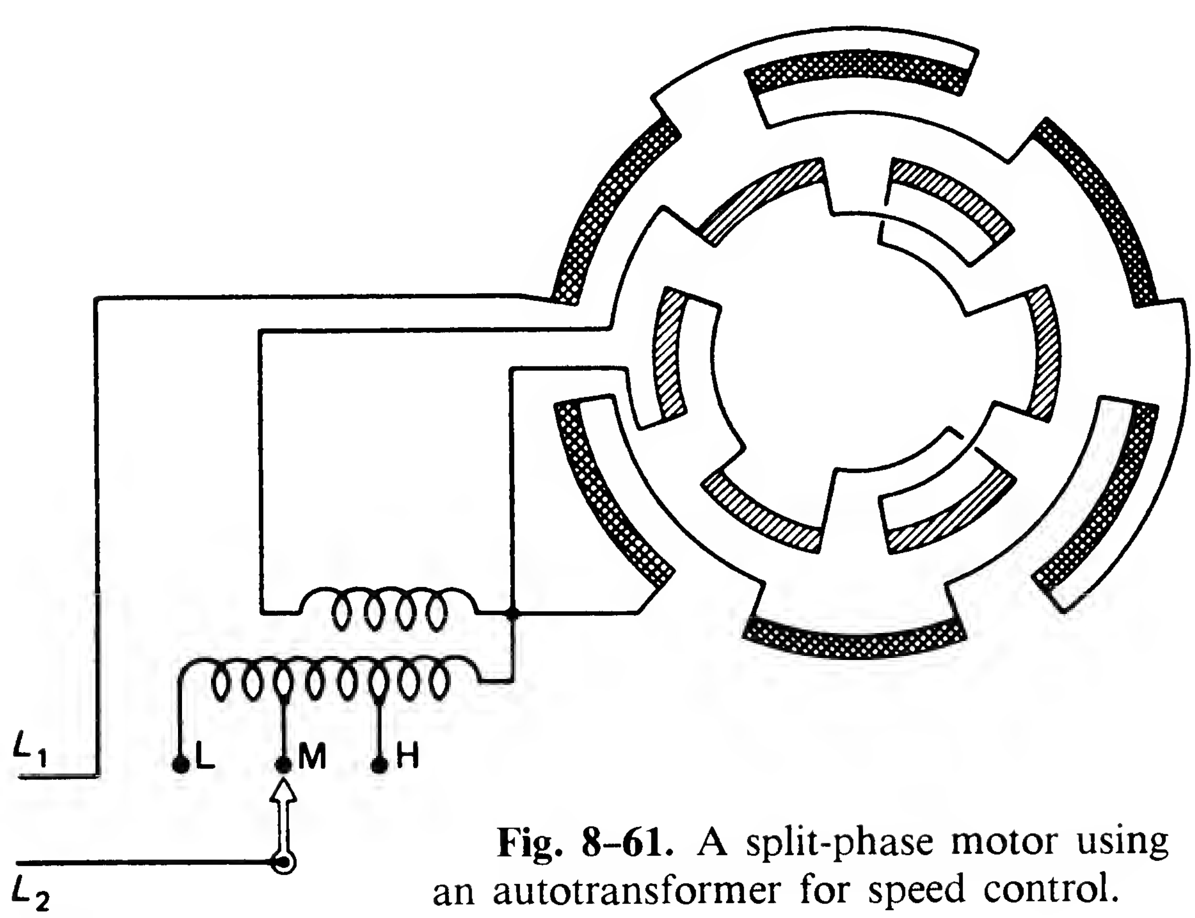


Fig. 8–61. A split-phase motor using an autotransformer for speed control.

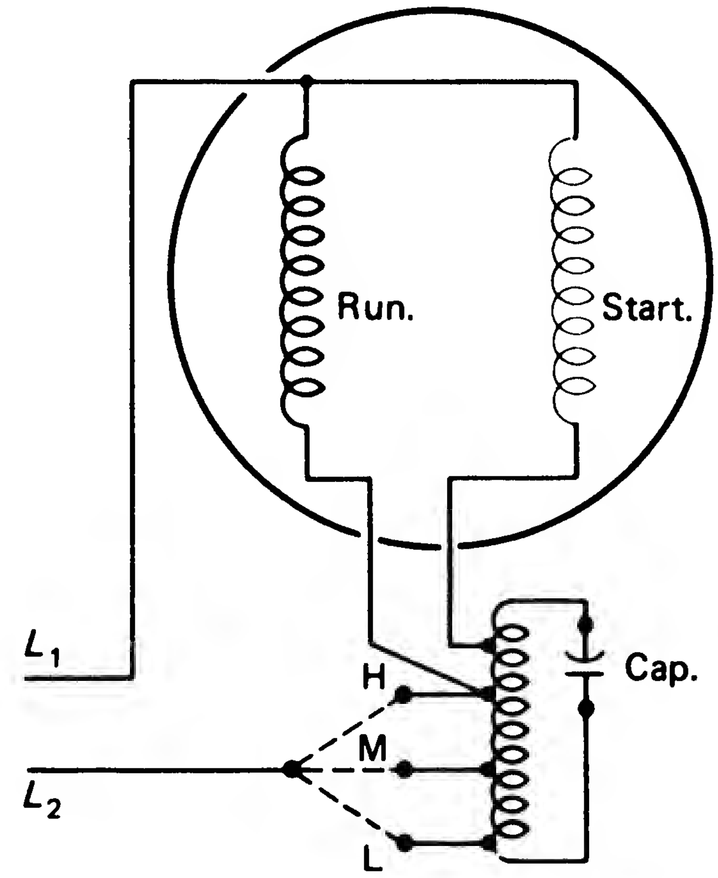


Fig. 8-62. Diagram of a capacitor motor used for fan service.

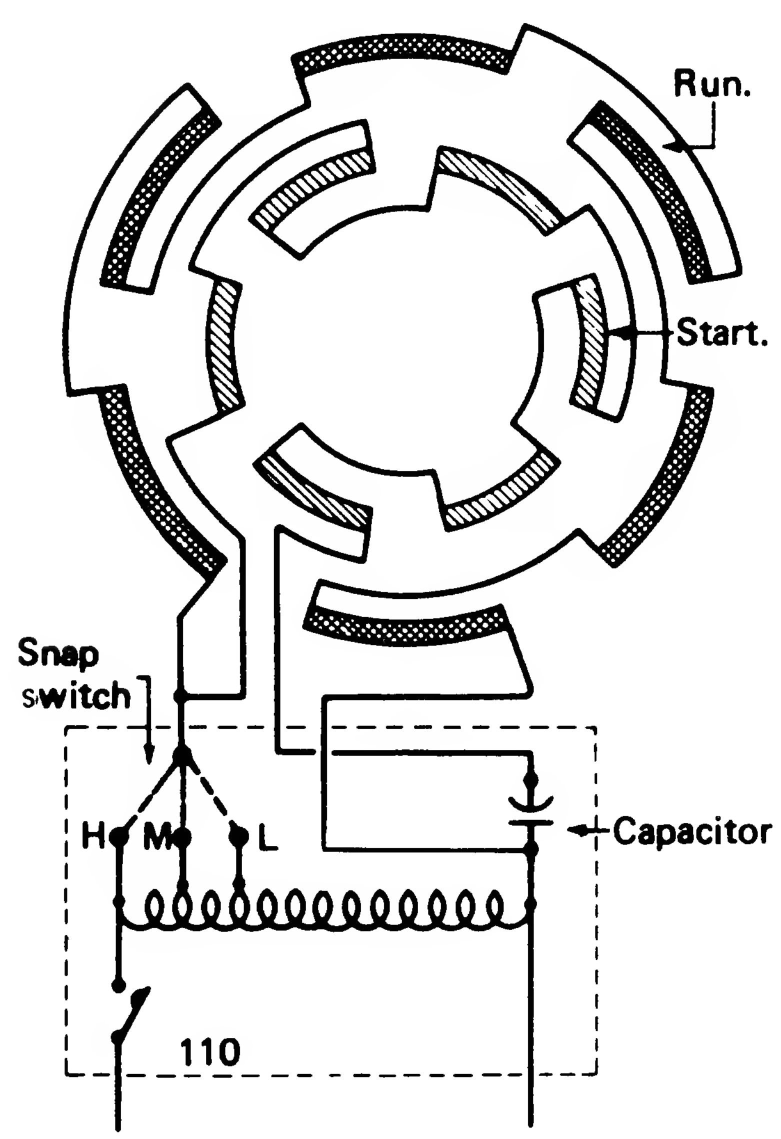


Fig. 8-63. Unit-heater three-speed motor. The speed is varied by impressing various voltages from an autotransformer to the running and starting windings.

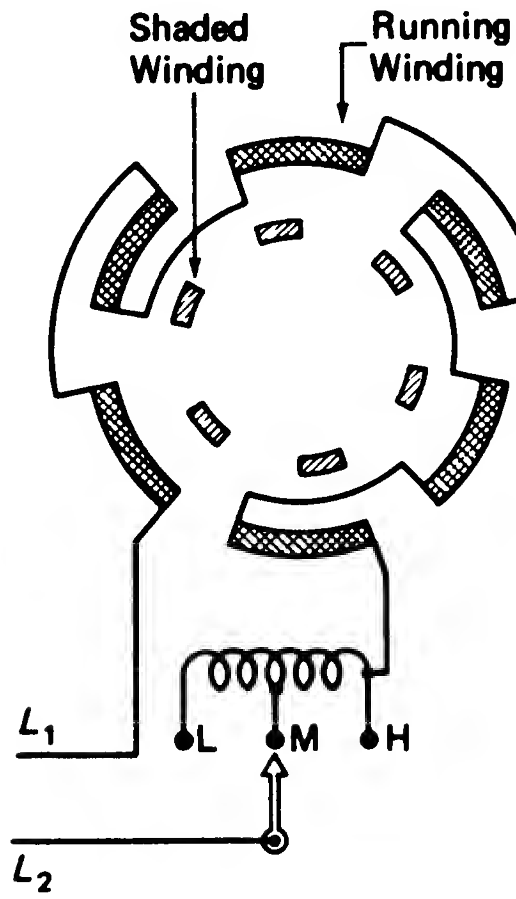
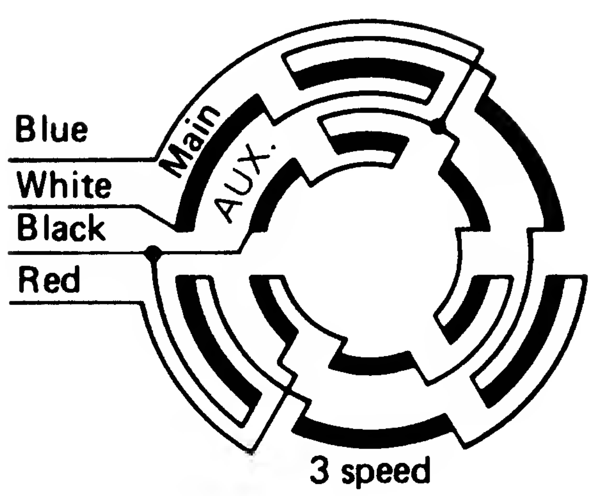


Fig. 8-64. Shaded-pole fan motor with speed control varied by means of a choke coil.



	L_1	L_2	Open
High speed	White	Black	Red,Blue
Int. speed	White	Blue	Red,Black
Low speed	White	Red	Blue,Black

Fig. 8-65. Three-speed shaded-pole motor.

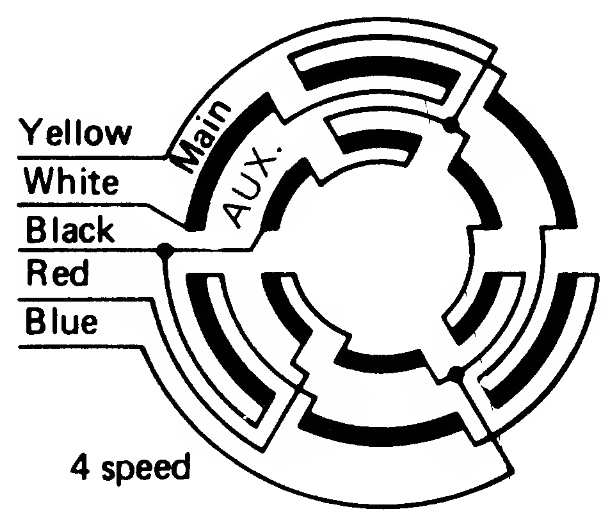


Fig. 8-66. Four-speed shaded-pole motor.

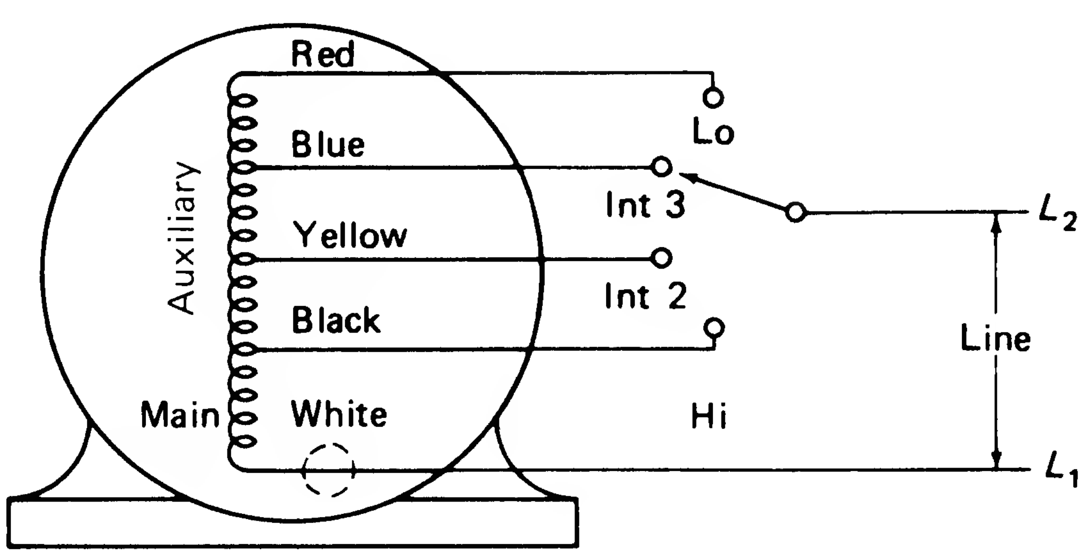


Fig. 8-67. External connection of a four-speed shaded-pole motor.

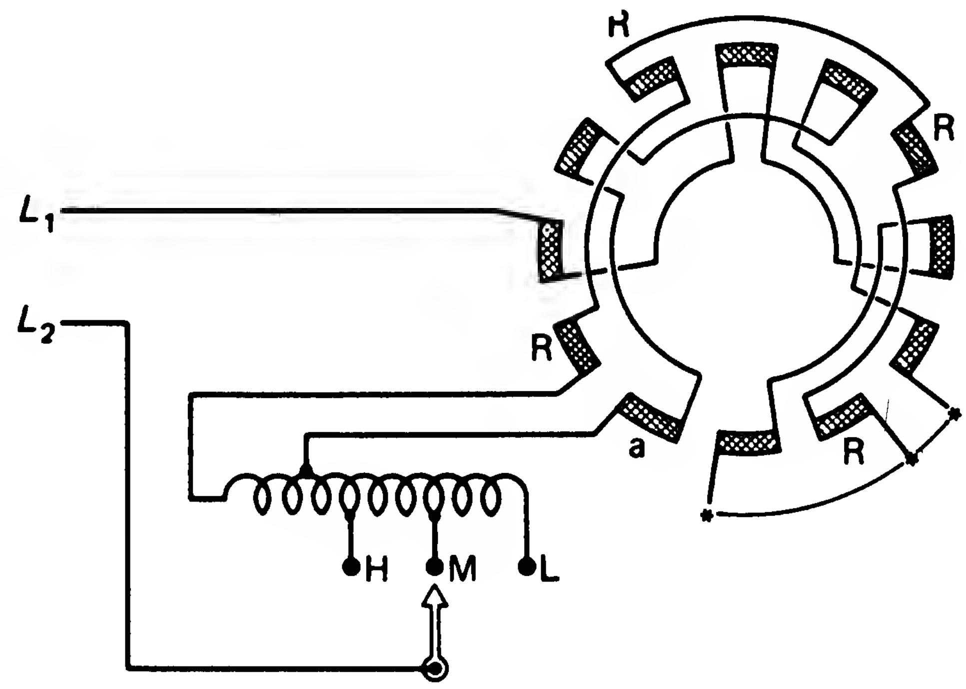


Fig. 8–68. A single-phase motor wound as a three-phase motor. By using resistance wire for the coils of one winding and a tapped-choke coil in series with another, this motor can be run at various speeds on a single-phase line.

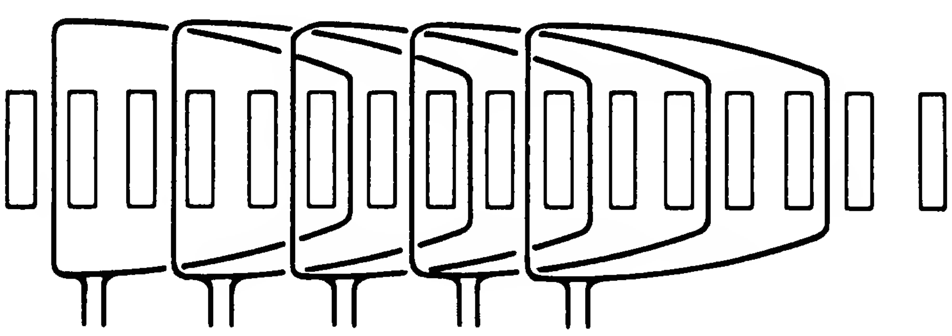


Fig. 8–69. Basket winding for a 48-slot, 24-coil, three-phase motor.

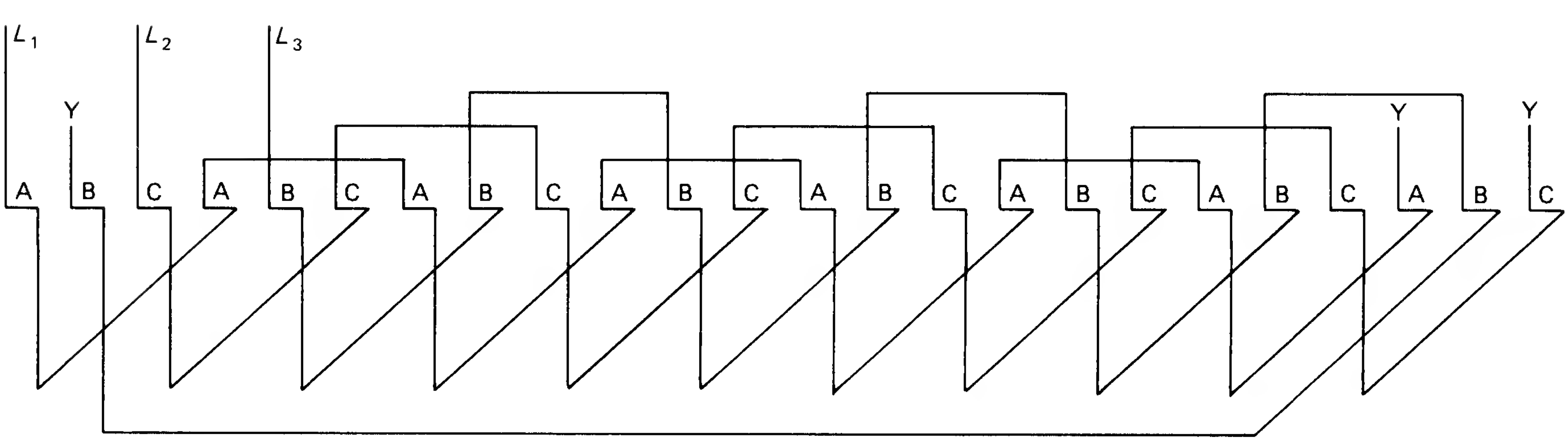


Fig. 8–70. A 48-slot, eight-pole, short jumper, three-phase motor connected in series-wye.

Figure 8–71

Westinghouse SMALL MOTOR SELECTION GUIDE

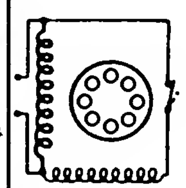
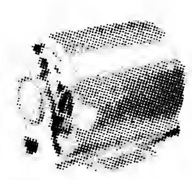
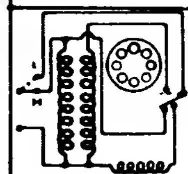
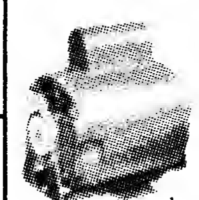
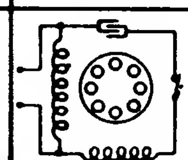
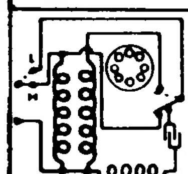
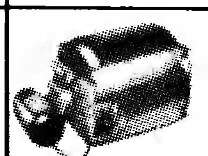
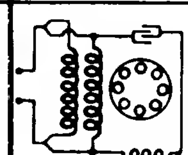
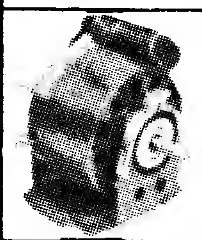
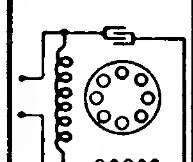
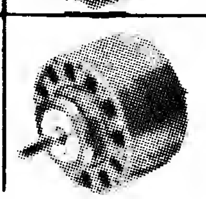
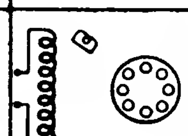
ALTERNATING CURRENT			TYPE OF MOTOR		WIRING DIAGRAM	TYPE	HP. Range	SPEED DATA: Rated Speed	SPEED DATA: Speed Characteristics	SPEED DATA: Speed Control	Approximate Torque (4-Pole Motors): Starting	Approximate Torque (4-Pole Motors): Break-down	Built-in Starting Mechanism	REVERSIBILITY: At Rest	REVERSIBILITY: In Motion	Radio Interference	Approximate Comparative Price	Bearings	Mountings	APPLICATION DATA
SINGLE PHASE	SPLIT PHASE		GENERAL PURPOSE	 RIGID MOUNTING		FH	1/20 to 3/4	3450 1725 1140 860	Constant	None	Medium to Low	Medium	Centrifugal Switch	Yes—Change Connections	No—Except with Special Design and Relay	None	85%	Sleeve or Ball	Various	For oil burners, office appliances, fans, blowers, low locked-rotor current minimizes light flicker making motor suitable for frequent starting. For applications up to 1/3 hp. where medium starting and breakdown torques are sufficient. Thermoguard available for ratings from 1/12 hp. up.
			HIGH TORQUE			FHT	1/16 to 1/2	1725	Constant	None	Medium	High	Centrifugal Switch	Yes—Change Connections	No—Except with Special Design and Relay	None	65%	Sleeve or Ball	Various	Ideal for washing machines, ironers, sump pumps, home workshops. For continuous and intermittent duty where operation is infrequent and locked-rotor current in excess of N.E.M.A. values is not objectionable. May cause light flicker on underwired or overloaded lighting circuits.
			TWO-SPEED (Two Windings)	 RESILIENT MOUNTING		FH	1/8 to 3/4	1725/1140 1725/860	Two-Speed	1-Pole Double-Throw Switch	Medium	Medium	Centrifugal Switch	Yes—Change Connections	No	None	165%	Sleeve or Ball	Various	For belted furnace blowers, attic ventilating fans, similar belted medium-torque jobs. Simplicity permits operation with any 1-pole, double-throw switch or relay. Starts well on either speed—thus used with thermostatic or other automatic control. Thermoguard recommended, as tight belt or incorrect pulley ratio may overload motor.
	CAPACITOR		GENERAL PURPOSE Capacitor-Start			FJ	1/6 to 3/4	3450 1725 1140 860	Constant	None	High	High	Centrifugal Switch	Yes—Change Connections	No—Except with Special Design and Relay	None	100%	Sleeve or Ball	Various	Ideal for all heavy-duty drives, such as compressors, pumps, stokers, refrigerators, air conditioning. All purpose motor for high starting torque, low starting current. Quiet, economical. High efficiency and power factor. Single voltage in 1/6, 1/4 hp., 1725 rpm. ratings—dual voltage in others. All sizes obtainable with thermoguard.
			TWO-SPEED Capacitor-Start (Two Windings)			FJ	1/6 to 3/4	1725/1140 1725/860	Two-Speed	1-Pole Double-Throw Switch	Medium	Medium	Centrifugal Switch	Yes—Change Connections	No	None	200%	Sleeve or Ball	Various	Supplements line of 2-speed split-phase motors (see Type FH, 2-speed). Used on identical applications requiring horsepower ratings from 1/3 to 3/4 hp.
			PERMANENT SPLIT (Single Value)			FL	1/20 to 3/4	1620 1080 820	Constant or Adjustable Varying	Two-Speed Switch or Autotransformer	Very Low	Low	None	Yes—Change Connections	Yes	None	155%	Sleeve or Ball	Resilient	For direct connected an drives . . . particularly unit heaters. Not for belt drives. Same motor adaptable for 115 or 230 volts for 1-speed, 2-speed, or multi-speed service by use of 1-pole, single-throw switch, 2-pole, double-throw switch, or speed controller, respectively. Fan load must be accurately matched to motor output for proper speed control. All ratings dual voltage and dual rotation.
			PERMANENT SPLIT Capacitor			FLL	1/25 to 1/4	1625 to 1075	Varying or Adjustable Varying	Tapped Winding or Choke Coil	Low	Low	None	Yes	Yes	None	—	Vertical Sleeve	Various	Companion to type FE shaded-pole motor. Their higher efficiency and power factor make this type motor ideal for driving fans in room air conditioners and window fans.
	SHADED POLE		SHADED POLE			FE	1/30 to 1/6	1550 1050	Constant or Adjustable Varying	Tapped Winding or Choke Coil	Very Low	Low	None	No	No	None	—	Sleeve	Rigid or Resilient	Constant speed, switchless motor for low-power applications. Used for fans, small blowers, unit heaters, hair driers. With fan load accurately matched to motor output, proper speed control can be obtained by means of series choke or resistance.

Fig. 8–71. Small motor selection guide. *(Westinghouse Electric Co.)*

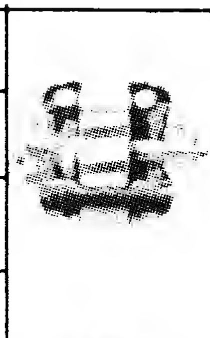
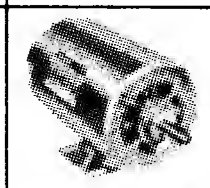
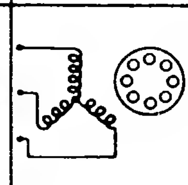
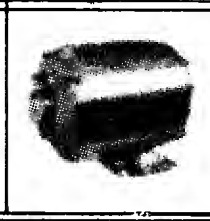
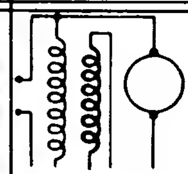
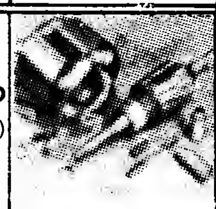
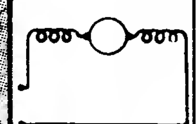
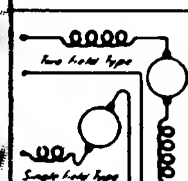
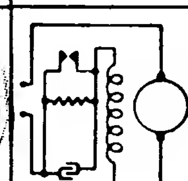
1, 2, 3 PHASE	SYNCHRONOUS	SPLIT-PHASE		Refer to FH	FBH	1/250 to 1/3	3600 1800 1200 900	Absolutely Constant	None	Low	Medium (See Note)	Centrifugal Switch	See FH	See FH	None	375%	Sleeve or Ball	Rigid	Used mostly on instruments, sound recording and reproducing apparatus, teleprinters, facsimile printers. Definitely constant speed. Type selected depends largely on starting torque. Type FBL recommended where low watts input desirable and low starting torque sufficient. Type FBH or FBJ recommended where higher starting torque needed. Pull-in torque on all types affected by inertia of connected load. Note: The "breakdown" torque refers to torque at point where motor speed drops below synchronous speed.
		CAPACITOR-START		Refer to FJ	FBJ					Medium	Medium (See Note)	Centrifugal Switch	See FJ	See FJ					
		PERMANENT SPLIT CAPACITOR		Refer to FL	FBL					Very Low	Medium (See Note)	None	See FL	See FL					
		POLYPHASE		Refer to FS	FBS					Medium	Medium (See Note)	None	See FS	See FS					
POLYPHASE	2 or 3 PHASE	SQUIRREL CAGE			FS	1/4 to 3	3450 1725 1140 860	Constant	None	High to Medium	Extra High	None	Yes—Change Connections	Yes—Change Connections	None	110%	Sleeve or Ball	Various	For all applications where polyphase circuits are available. Special designs with extra high starting torque for hoists, door operators, tool traverse and clamp devices. High frequency motors are used for high speed applications such as rayon spinning machines and portable tools.
D-C		SHUNT WOUND AND COMPOUND WOUND			FK	1/12 to 3/4	3450 1725 1140 860	Constant or Adjustable Varying	Armature Resistance	Extra High	—	None	Yes—Change Connections	No—Except with Special Design	Yes	195%	Sleeve or Ball	Rigid or Resilient	For all applications operated from D-C circuits. Companion D-C motor to single phase and polyphase A-C motors. Ratings of 1/12 hp., 1725 rpm. and smaller shunt-wound. Larger ratings compound wound. Starting rheostats recommended for ratings 1/2 hp. and up.
A-C OR D-C	UNIVERSAL	NON-COMPENSATED (Salient Pole Winding)				1/150 to 3/4	1500 to 15000	Varying	Voltage Control Using Resistance or Transformer	Extra High	—	None	No—Except with Special Design	No—Except with Special Design	Yes	—	Sleeve	Rigid	Especially suitable for sewing machines, portable tools, vacuum cleaners, motion picture projectors, and mixers. Operates on A-C or D-C circuits. Inherent characteristics are high-starting torque, high speed, varying speed regulation and small size and light weight for given hp. output.
		COMPENSATED (Distributed Winding)				1/40 to 2 1/2	2500 to 15000	Varying		Extra High	—	None	No—Except with Special Design	No—Except with Special Design	Yes	—	—	—	Compensated parts recommended when higher power at lower speeds required as for larger commercial type vacuum cleaners, large portable tools. Wide variety of electrical characteristics and housing designs available.
		GOVERNOR CONTROLLED				1/50 to 1/8	2000 to 7500	Adjustable Constant	Adjustable Governor	Extra High	—	None	No—Except with Special Design	No—Except with Special Design	Yes	—	Sleeve	Rigid	Governor permits utilizing light-weight, high-speed, universal motor for constant speed applications. Two types governors supplied. One permits adjustment while running—used on electric typewriters, motion picture projectors, cameras. Other type adjustable at standstill only—used for adding machines, calculating machines, other constant speed office machines.

Fig. 8-71. Small motor selection guide (*continued*). *(Westinghouse Electric Co.)*

Figures **8**–71 (*con't.*)

CHAPTER 9

Direct-current Generators; Synchronous Motors and Generators; Synchros; and Wound Rotor, Three-phase Induction Motors

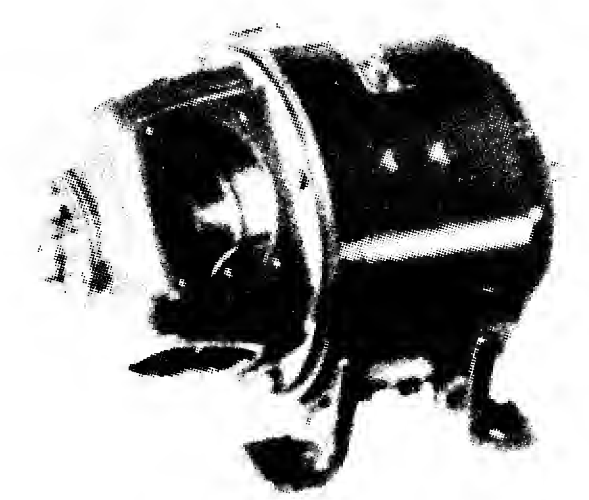


Fig. 9-1. A dc generator.

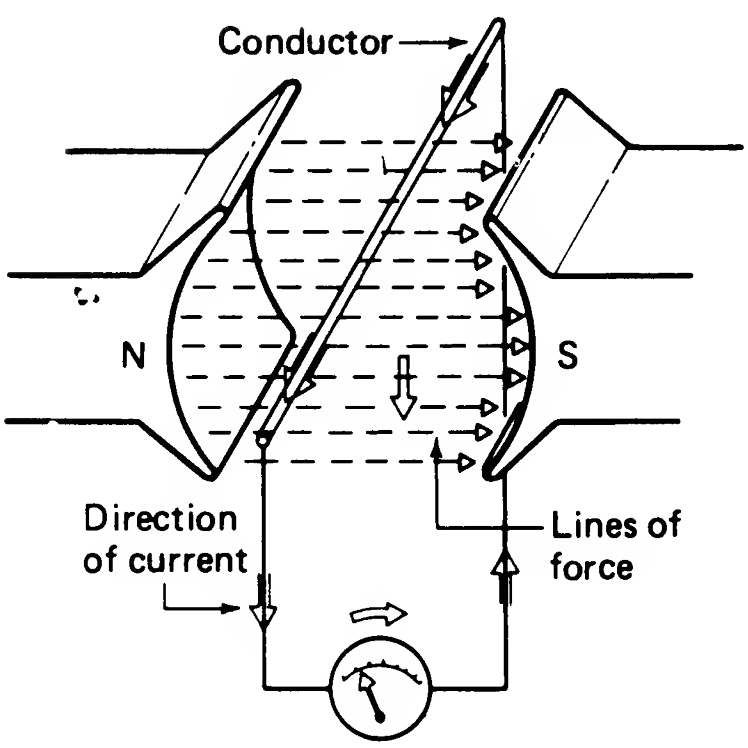


Fig. 9-2. A potential is induced in the conductor when it cuts lines of force.

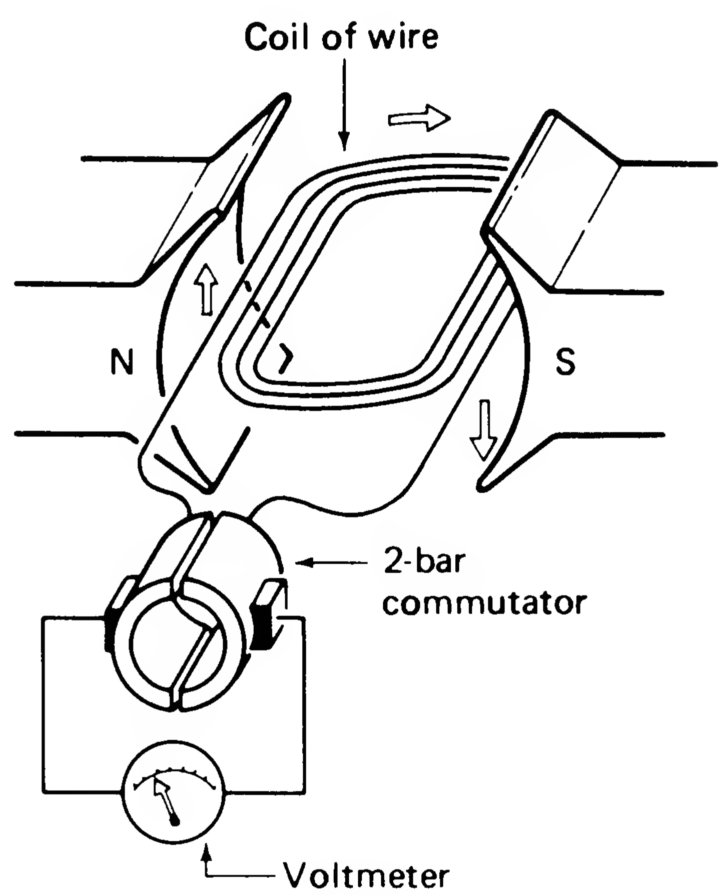


Fig. 9-3. A coil of wire used as the conductor and rotated in a magnetic field. The leads of the coil are connected to a commutator to produce direct current.

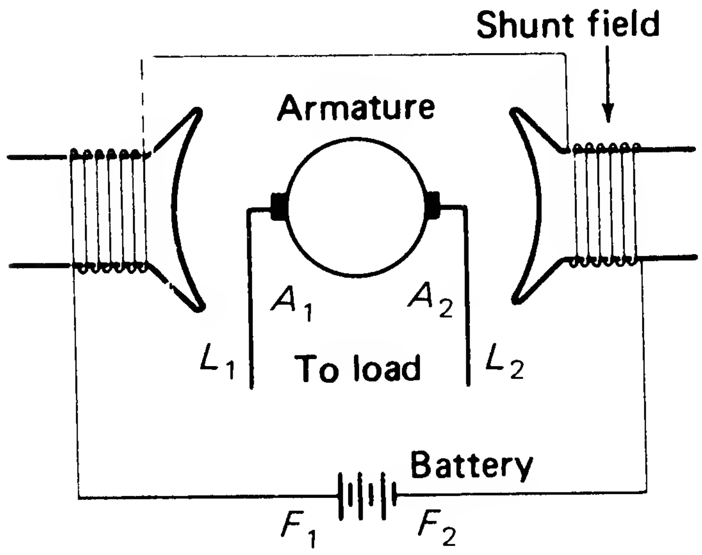


Fig. 9–4. A separately excited shunt generator.

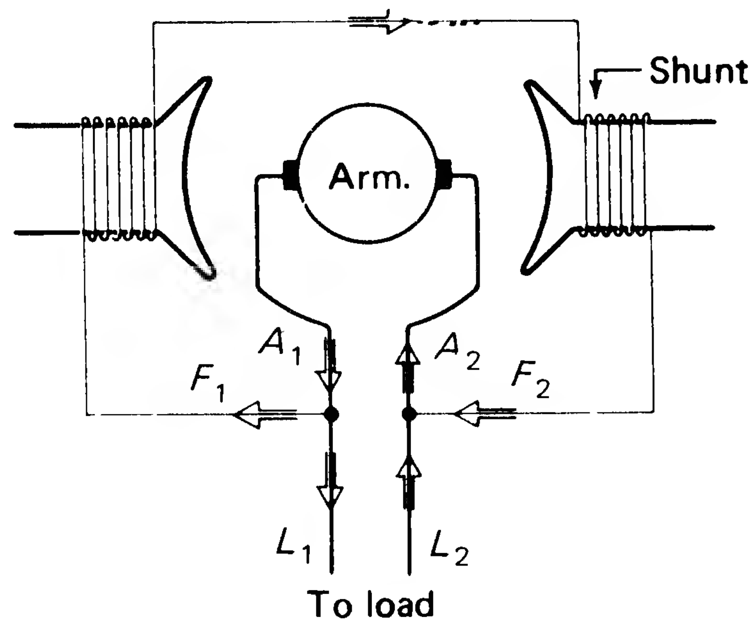


Fig. 9–5. A self-excited shunt generator.

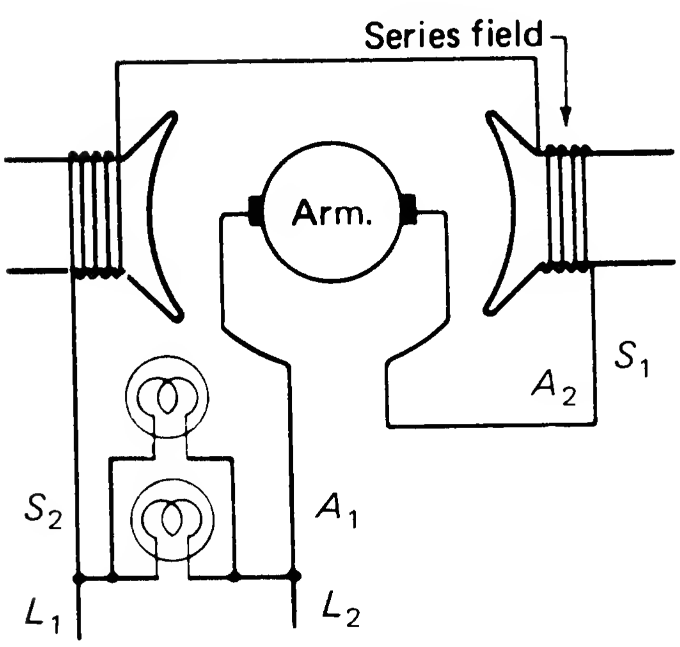


Fig. 9–6. A self-excited series generator.

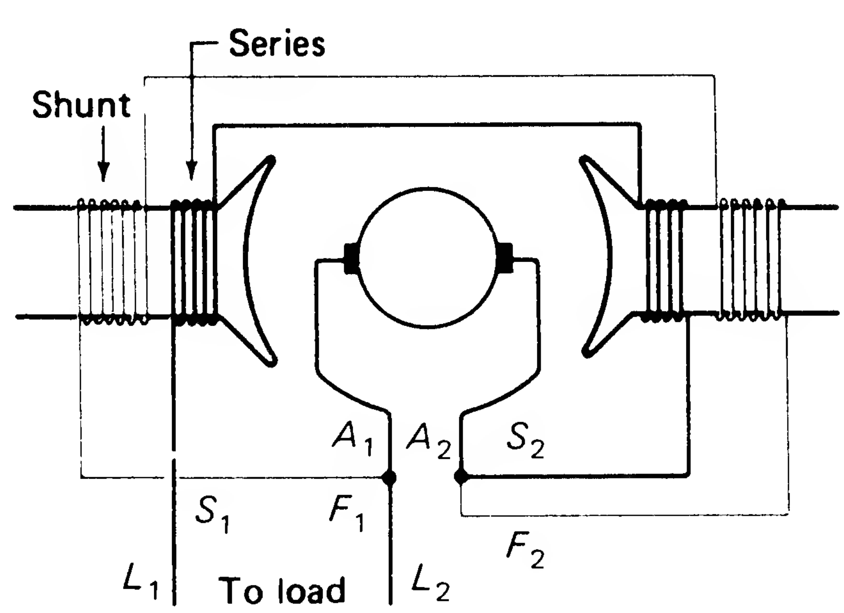


Fig. 9–7. A short-shunt cumulative compound generator.

Figures 9–4; 9–5; 9–6; 9–7

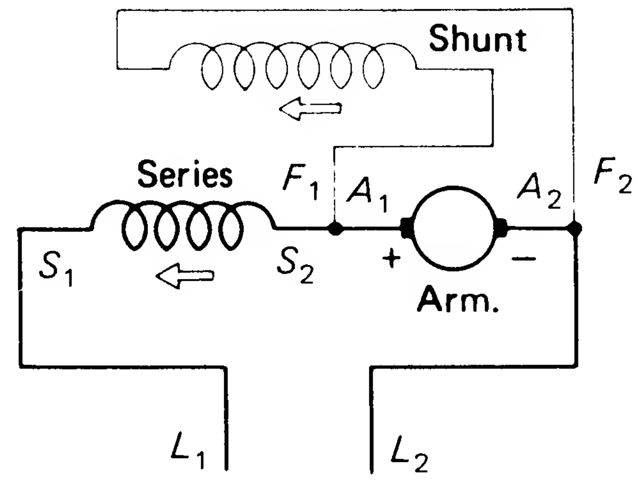


Fig. 9–8. Wiring of a compound short-shunt generator.

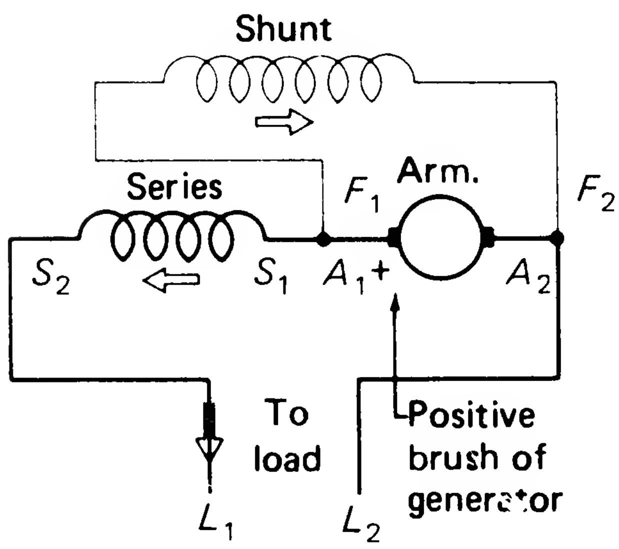


Fig. 9–9. A short-shunt differential generator.

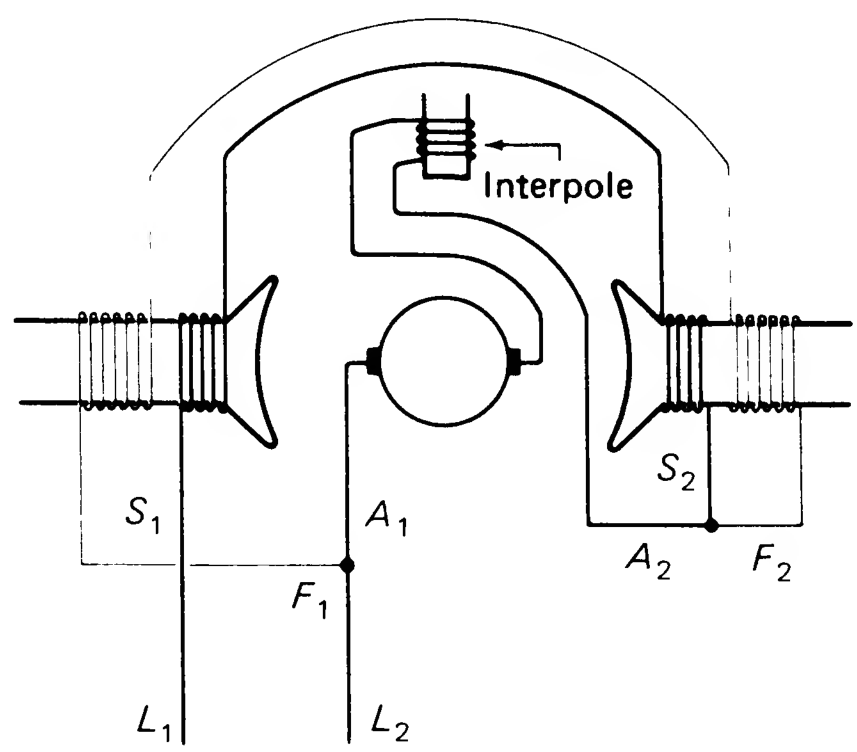


Fig. 9–10. A short-shunt cumulative generator with interpole.

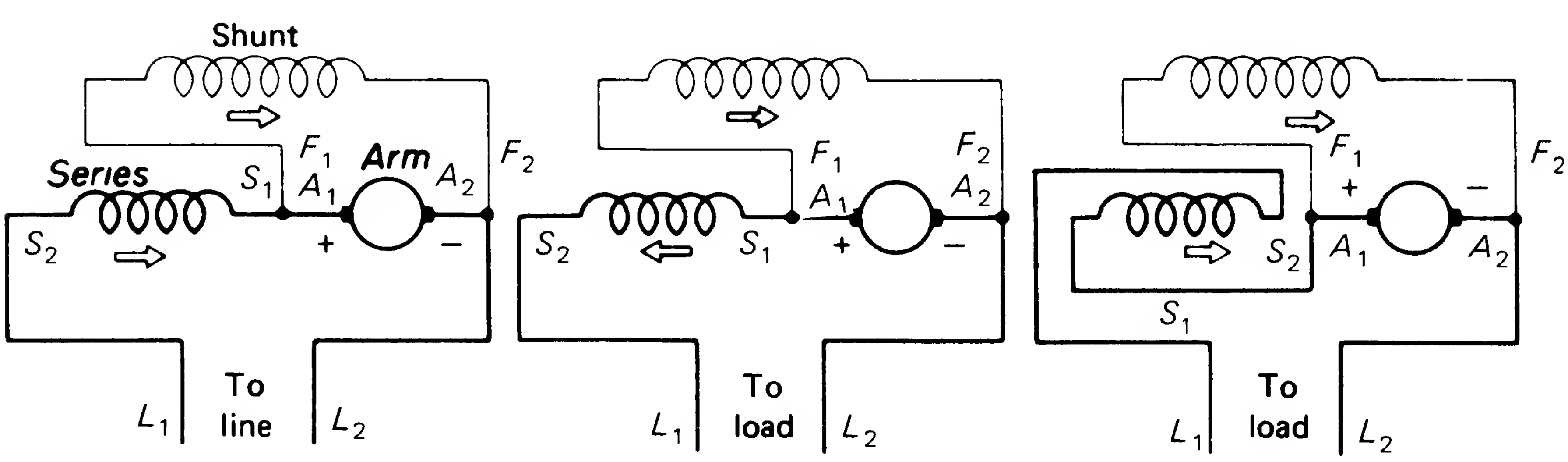


Fig. 9–11. At the left is shown the direction of flow of the two field currents of a compound motor. This motor is cumulative, but if used as a generator, it will be differential, as shown in the center. If the series field is reversed, as shown at the right, the generator will be cumulative.

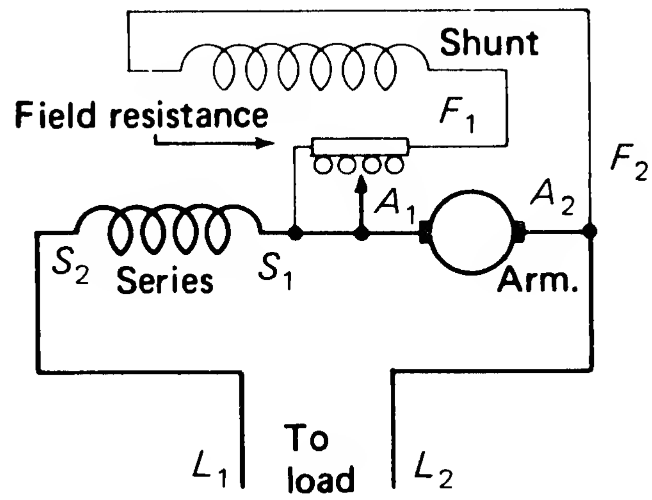


Fig. 9–12. A short-shunt cumulative generator with field rheostat for voltage control.

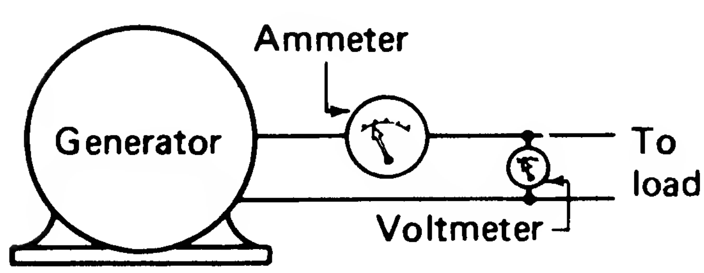
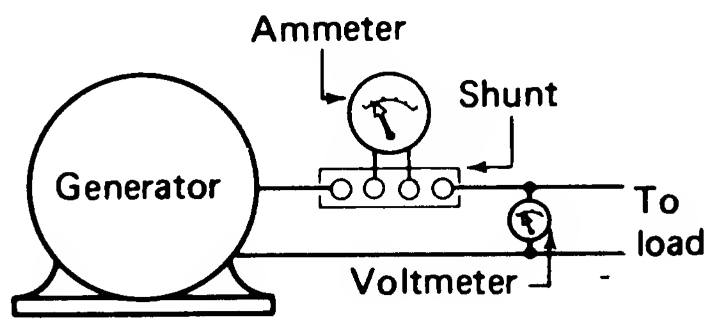


Fig. 9–13. A voltmeter and an ammeter properly connected in a generator circuit.

Fig. 9–14. An ammeter with external shunt connected in generator circuit.



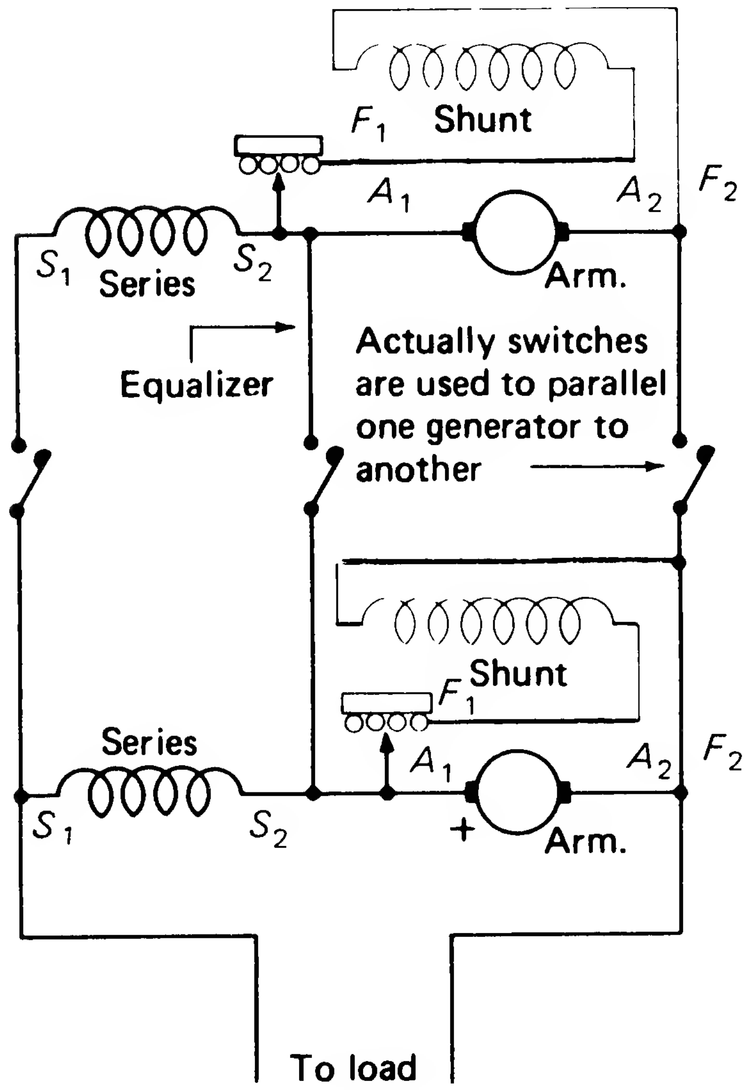


Fig. 9–15. Two compound generators connected in parallel.

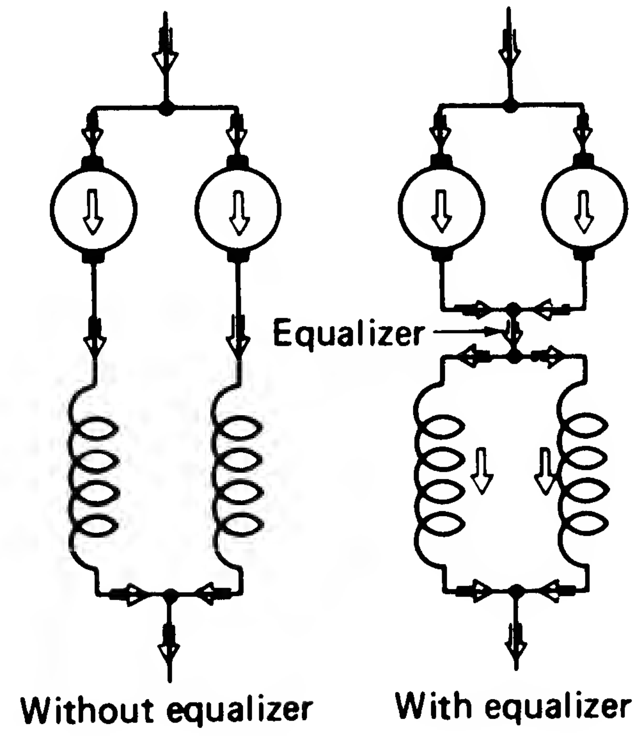


Fig. 9-16. A diagram showing how the load is divided equally between two generators if equalizer is used.

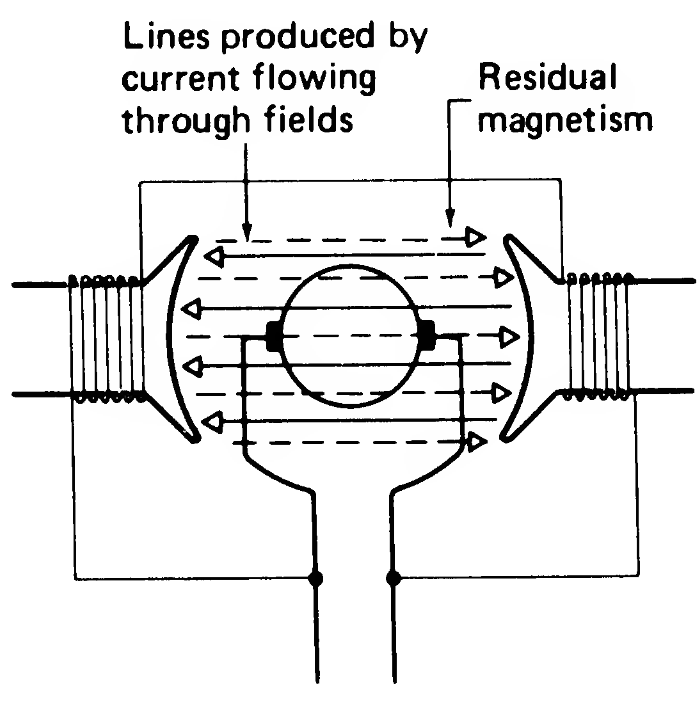


Fig. 9-17. An incorrect connection of shunt field in a generator. The residual lines of force oppose the lines caused by the field current and prevent build-up of the field strength.

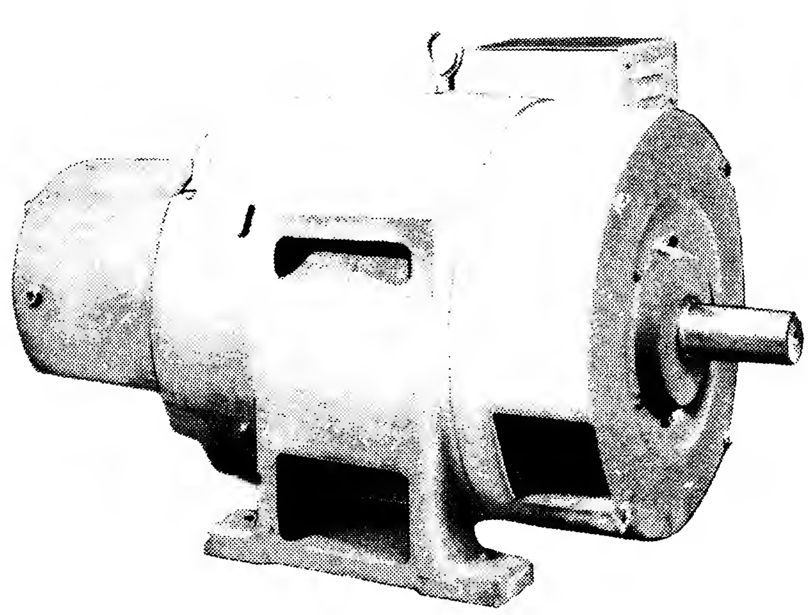


Fig. 9-18. A synchronous motor for general-purpose application. *(General Electric Co.)*

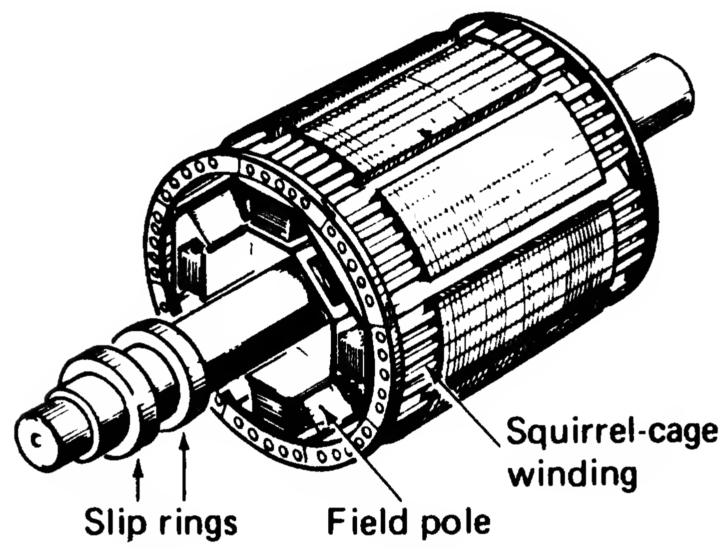


Fig. 9–19. A rotor of a synchronous motor.

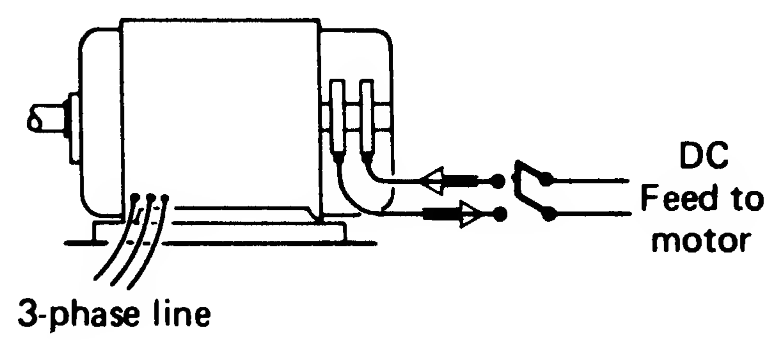


Fig. 9–20. Synchronous-motor power connections.

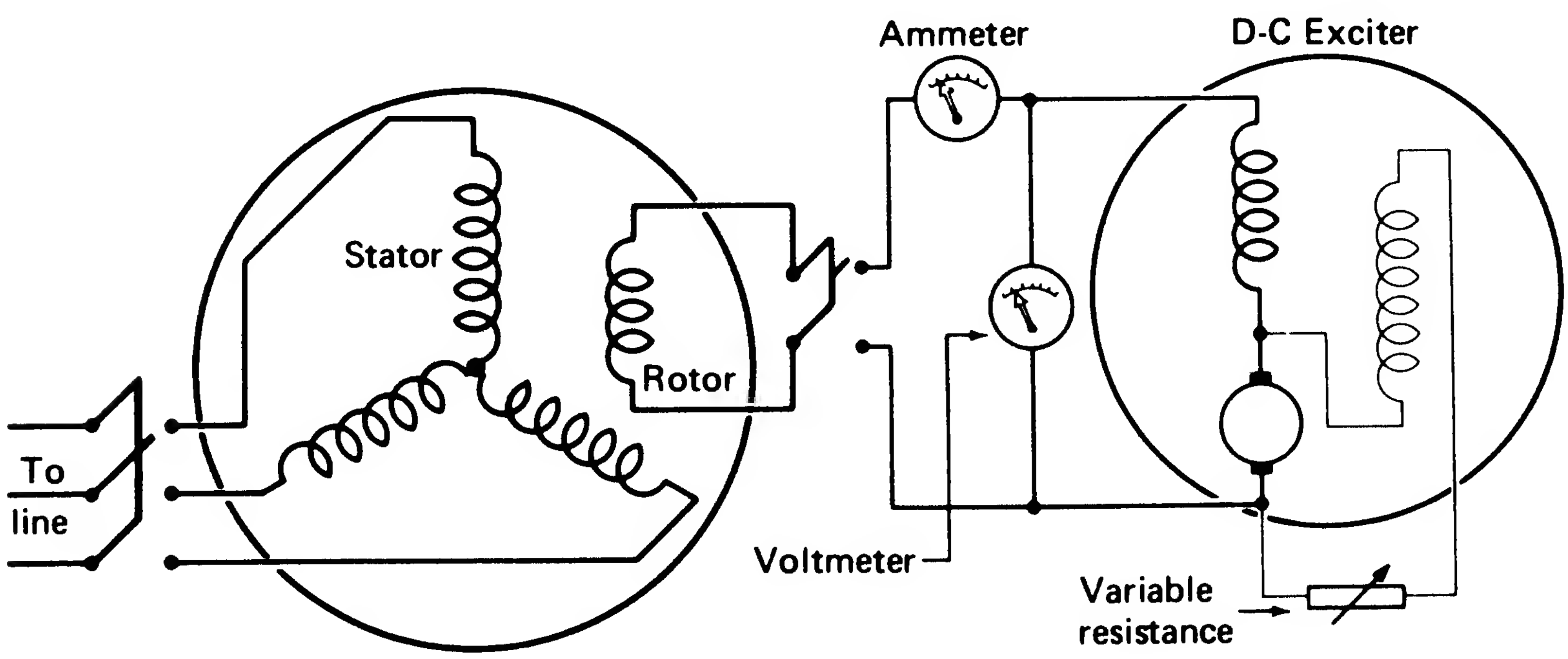


Fig. 9–21. A synchronous motor showing rotor supplied from a small exciter.

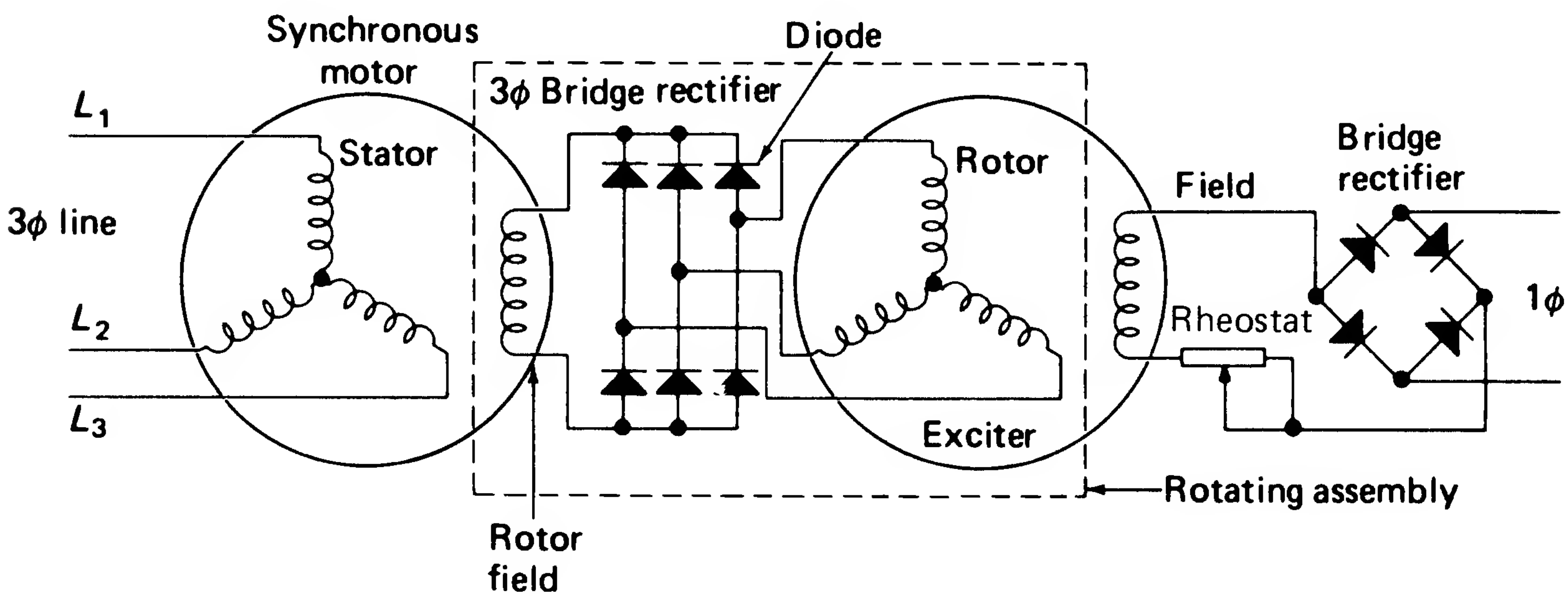


Fig. 9–22. Connections for a brushless synchronous motor.

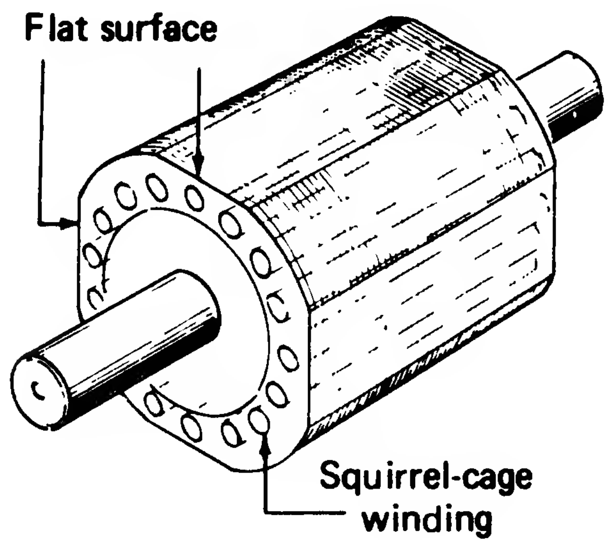


Fig. 9–23. A flat-faced rotor of a self-starting, nonexcited, split-phase synchronous motor.

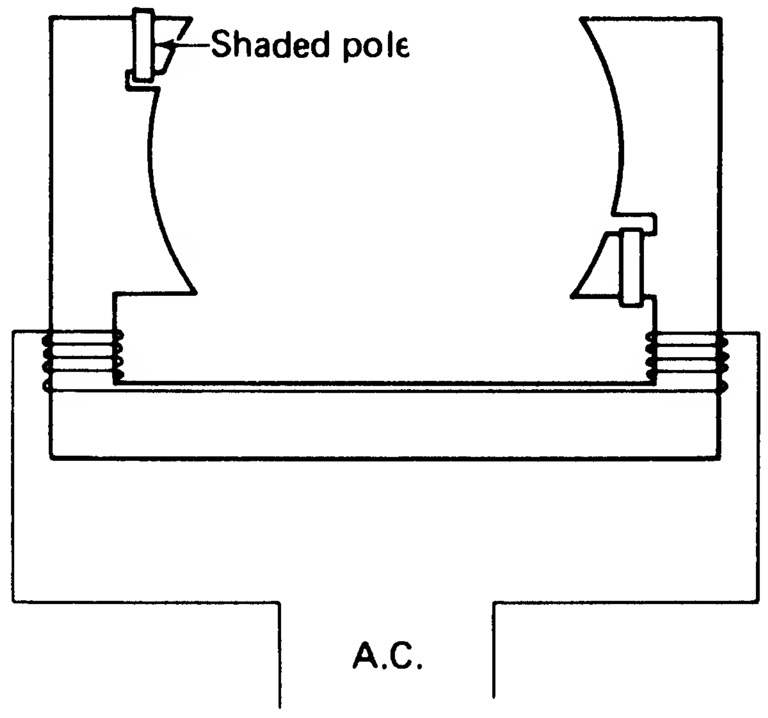


Fig. 9–24. A stator with shaded poles for a synchronous clock motor.

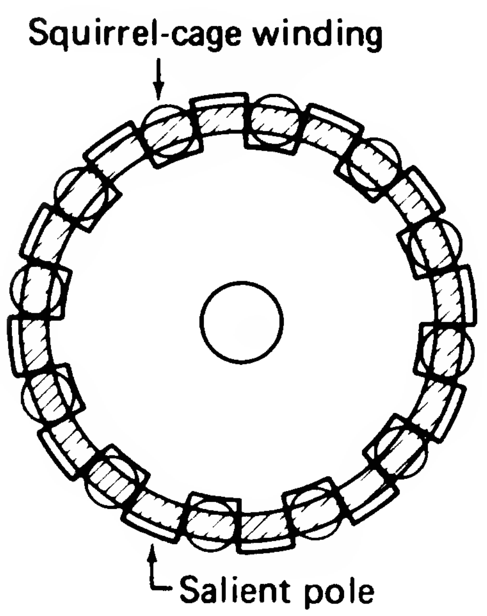


Fig. 9–25. A rotor for a self-starting synchronous motor.

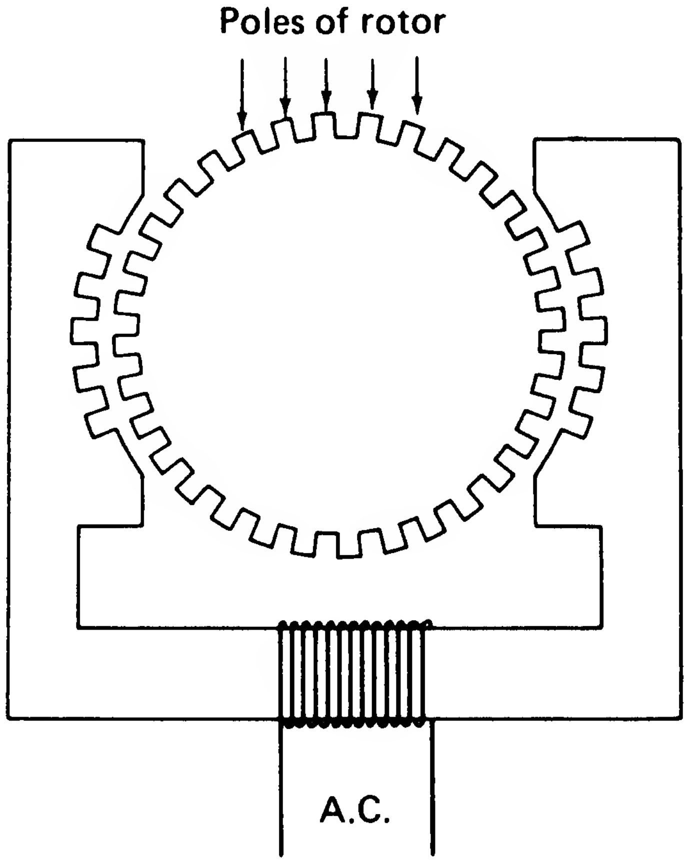


Fig. 9–26. A synchronous clock motor having 32 poles.

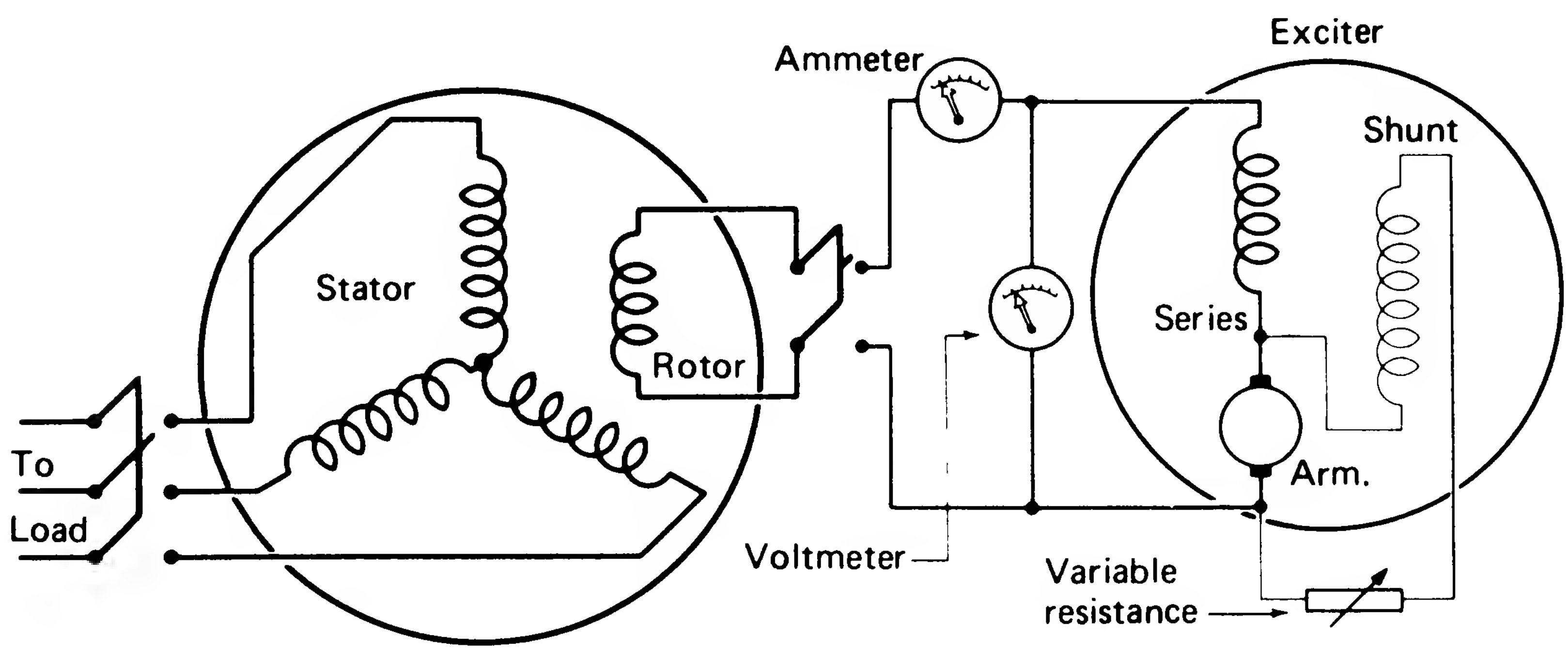


Fig. 9–27. Synchronous-generator connections.

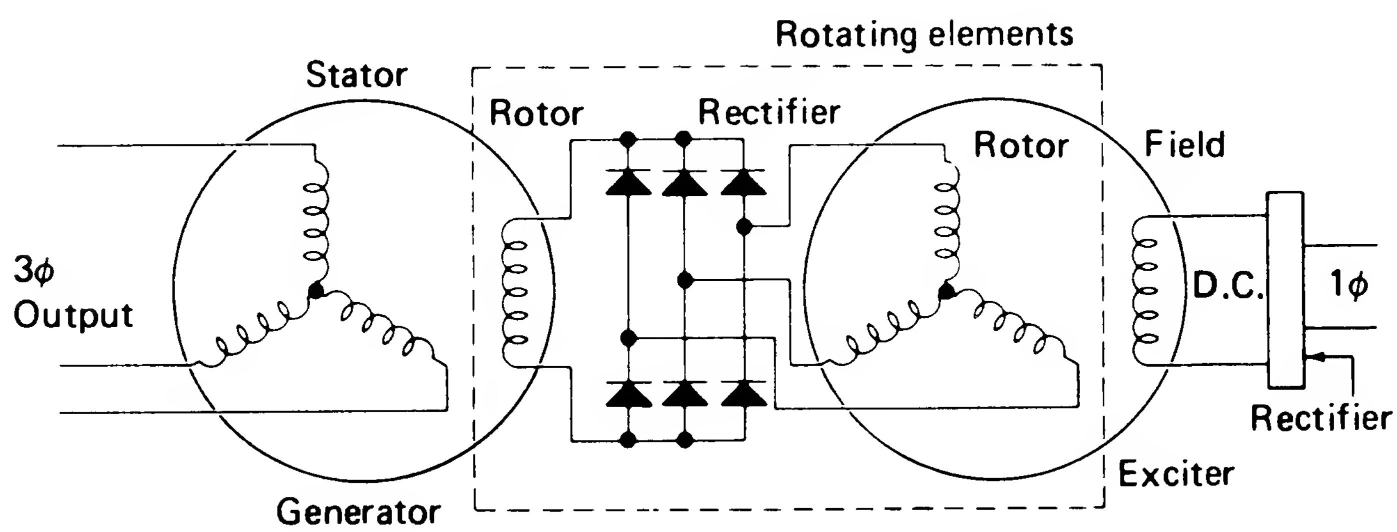


Fig. 9–28. Elementary diagram of a brushless synchronous generator.

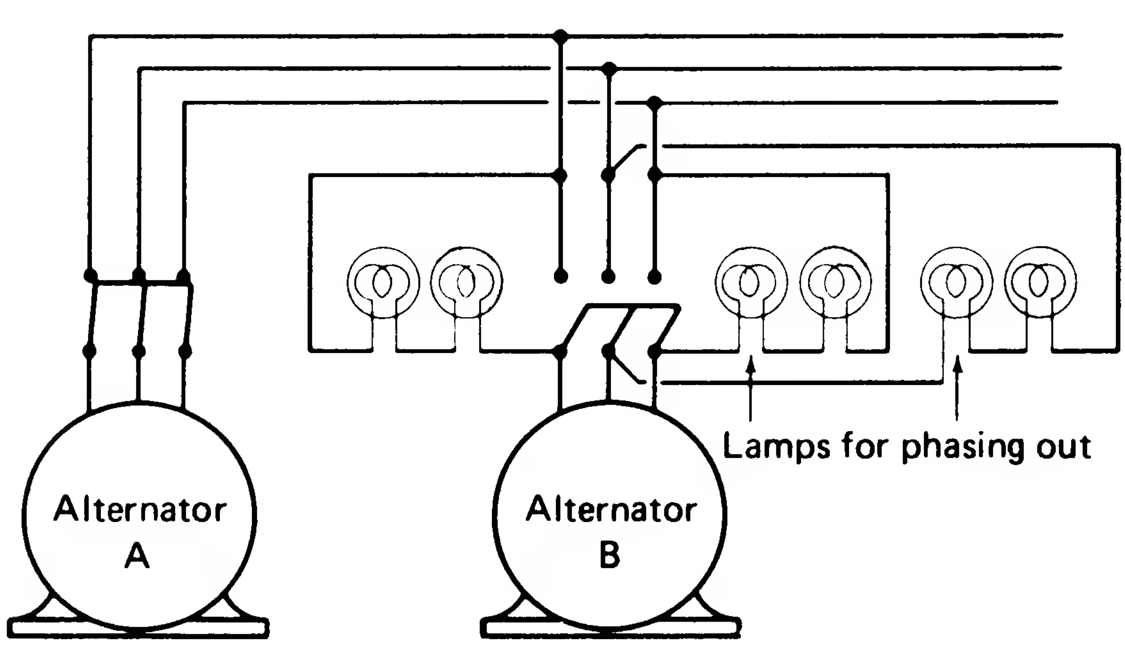


Fig. 9–29. The "all dark" method of synchronizing two alternators.

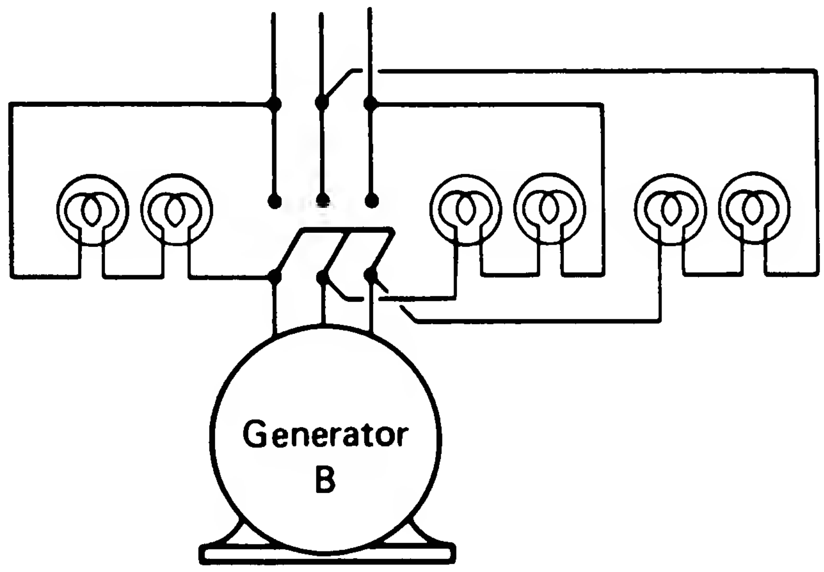
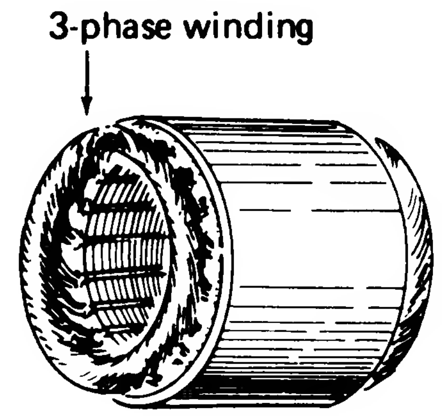


Fig. 9–30. The "one dark and two bright" method of synchronizing.

Fig. 9–31. A stator of a synchro.



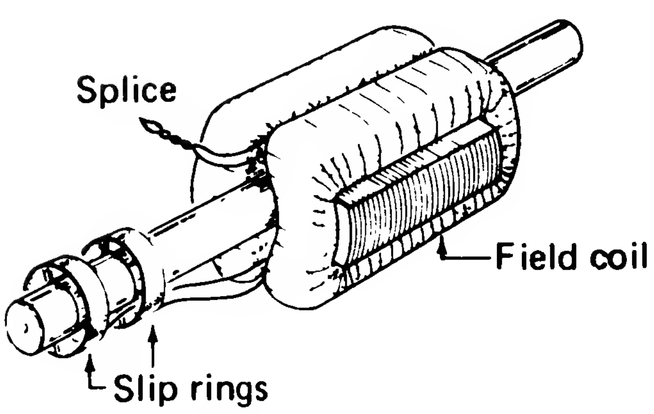


Fig. 9–32. A rotor of a synchro.

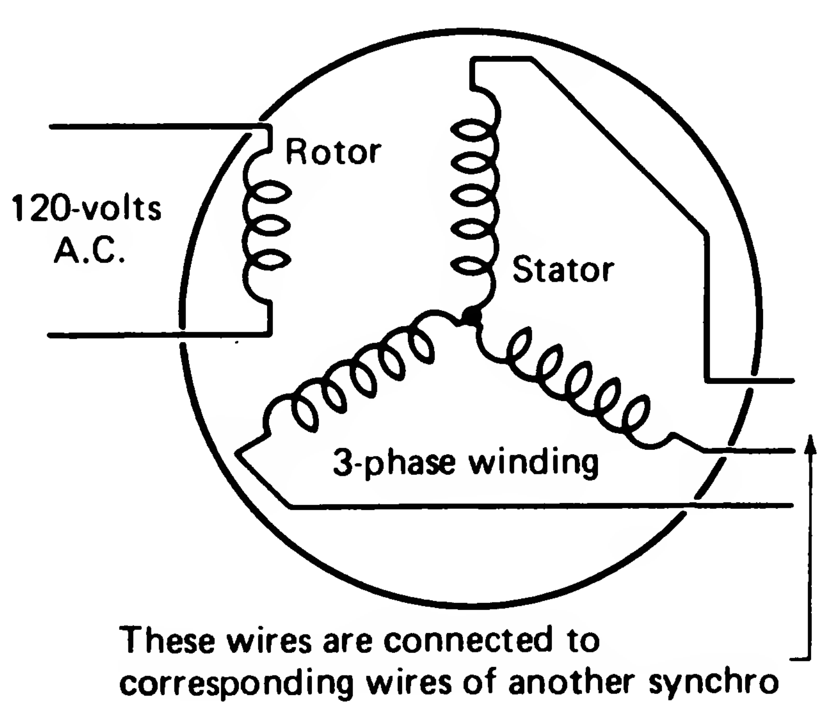


Fig. 9–33. Connections of a synchro showing a three-phase winding on the stator and a single-phase winding on the rotor.

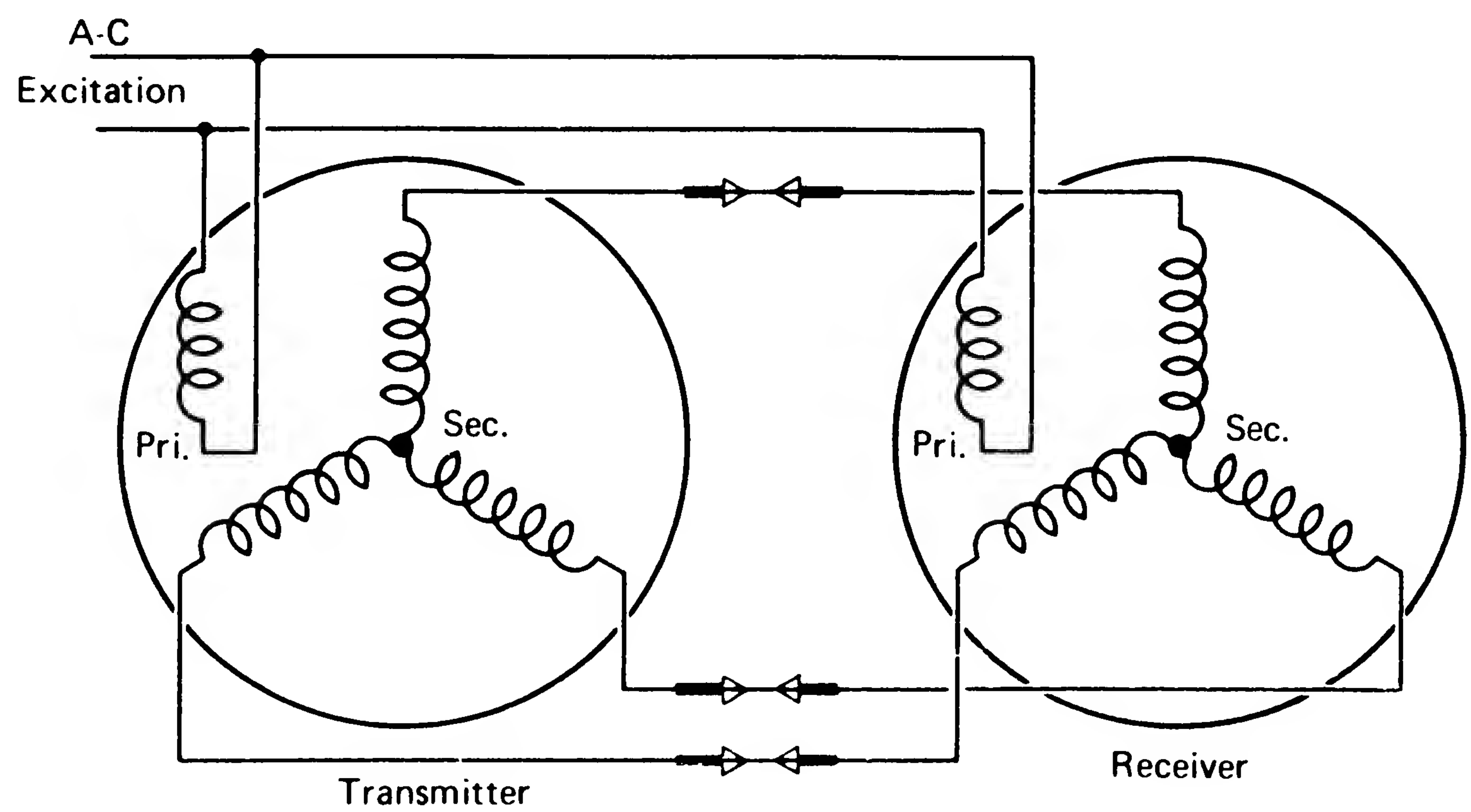


Fig. 9-34. Two synchros connected for operation. The receiver will remain motionless until the transmitter is turned.

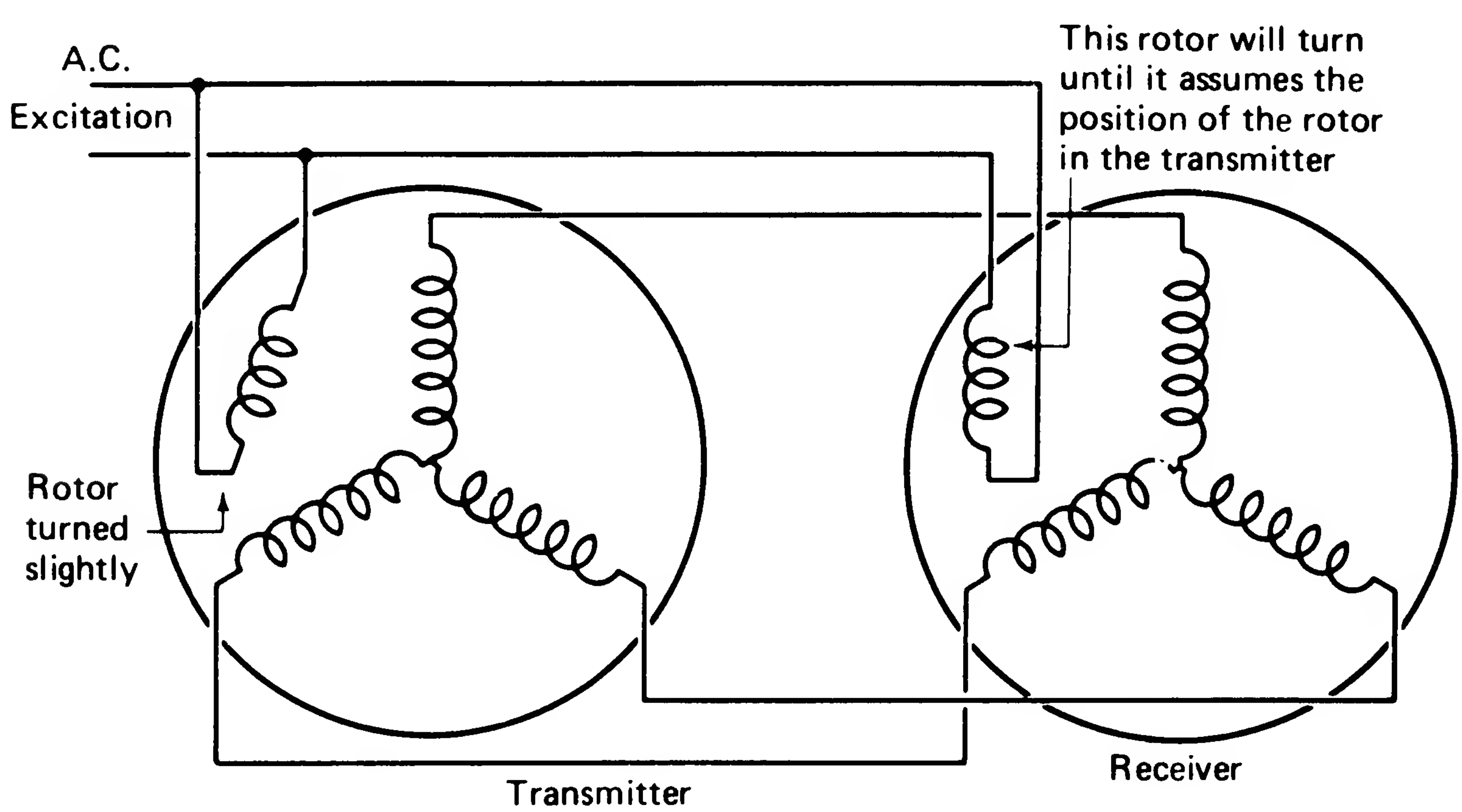


Fig. 9-35. The rotor of the transmitter has been turned slightly, causing the receiver to turn.

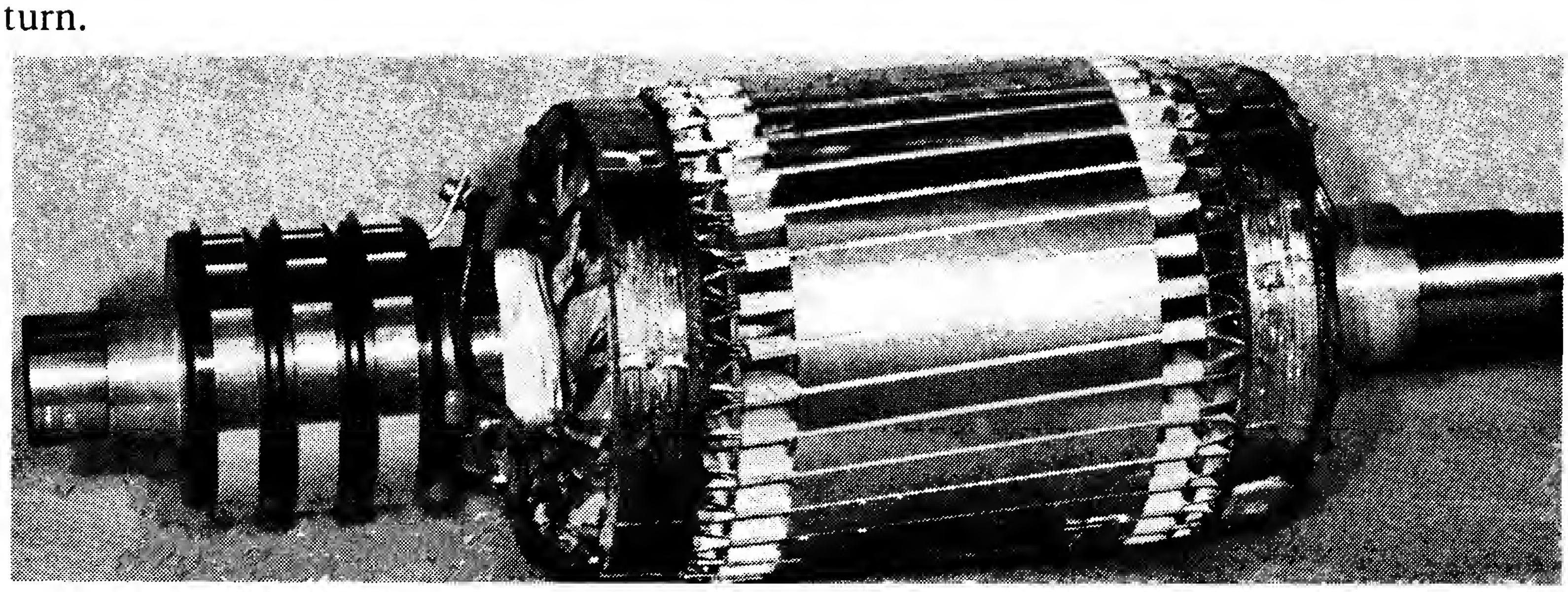


Fig. 9-36. A rotor of a wound-rotor, three-phase induction motor. *(Westinghouse Electric Co.)*

Figure 9-34; 9-35; 9-36

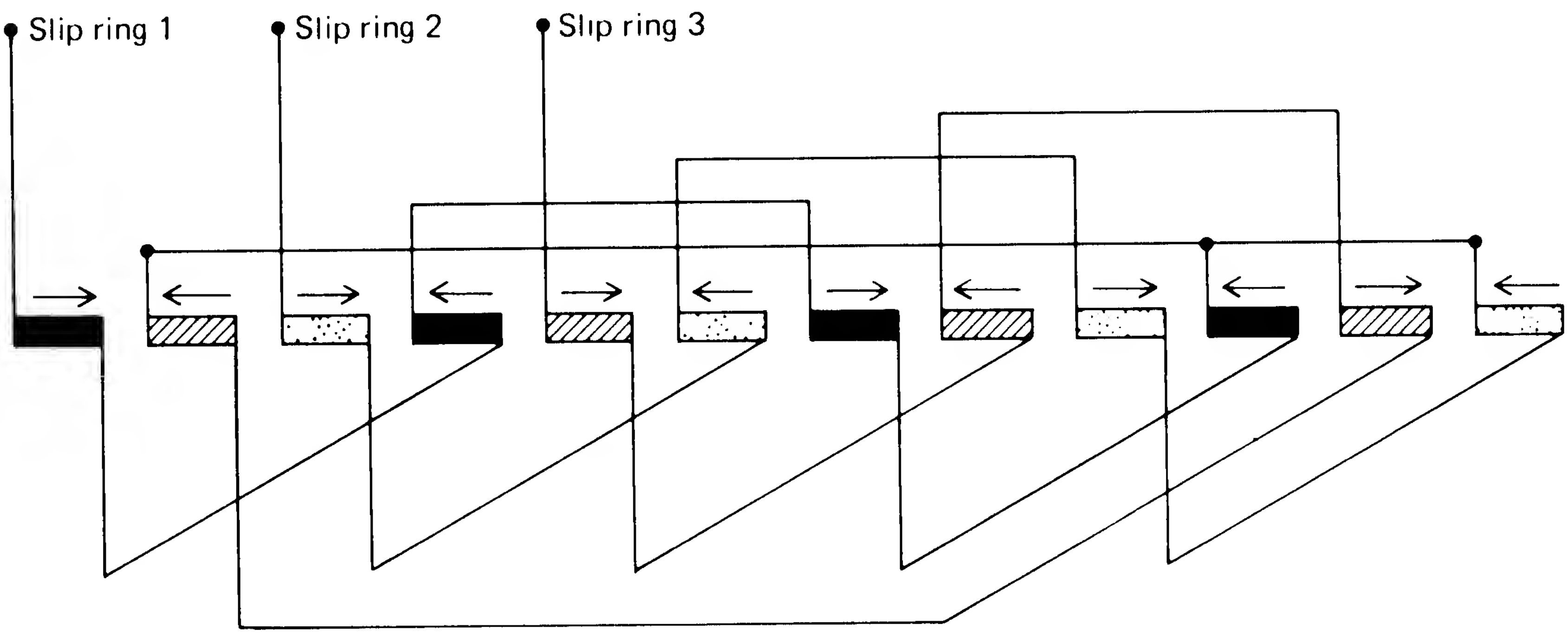


Fig. 9–37. A one-wye connection used in the rotor of a wound-rotor, three-phase induction motor.

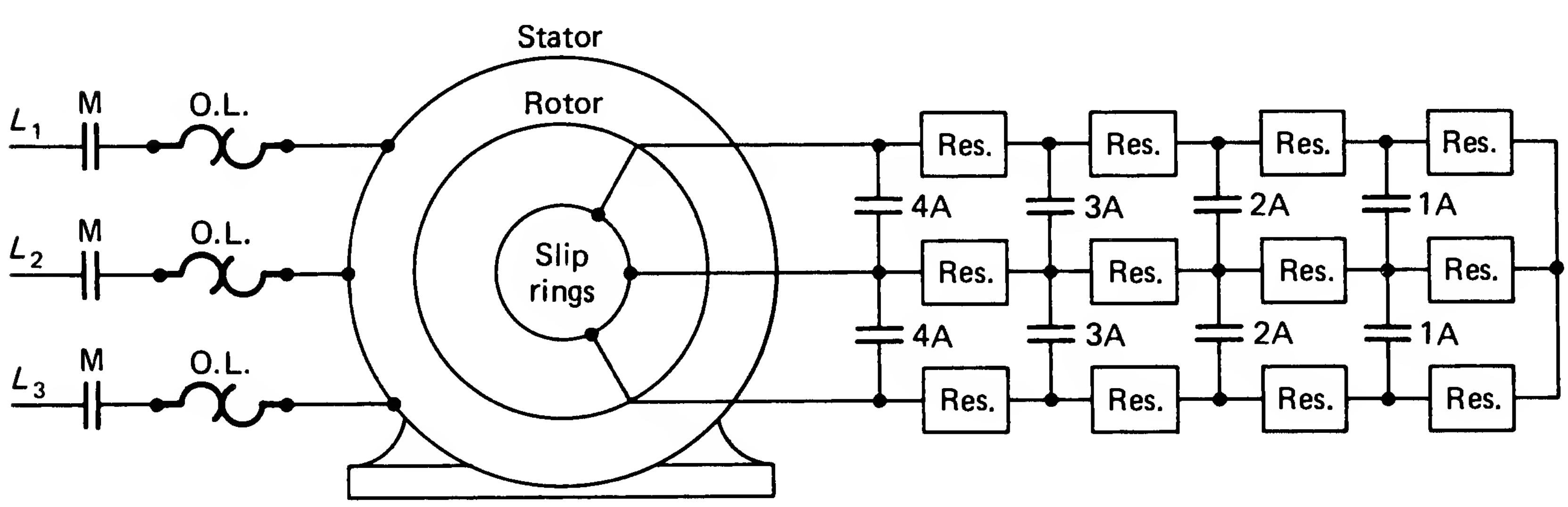


Fig. 9–38. An elementary diagram of a four-step resistance starter for a wound-rotor, three-phase induction motor without the controlling circuit.

CHAPTER 10

Solid-state Motor Control

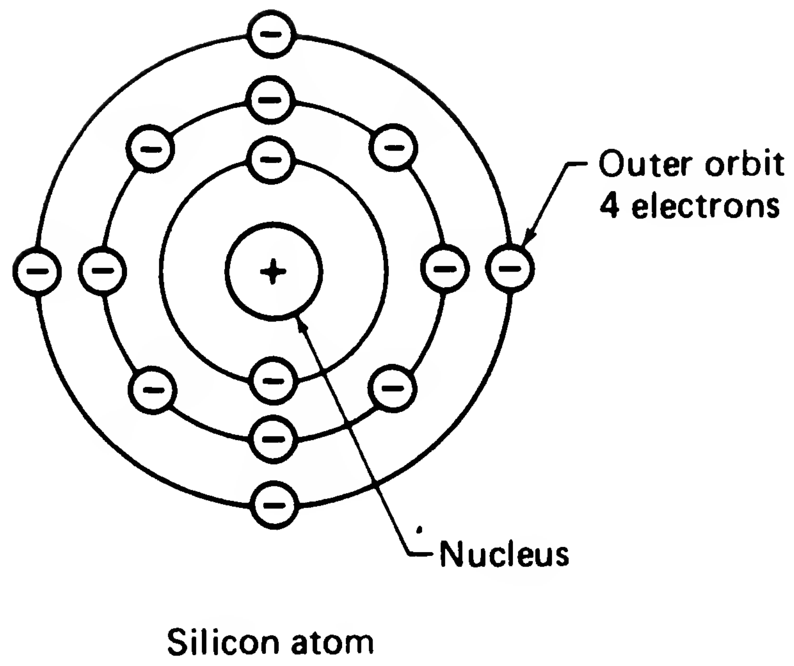


Fig. 10-1. Bohr model of a silicon atom.

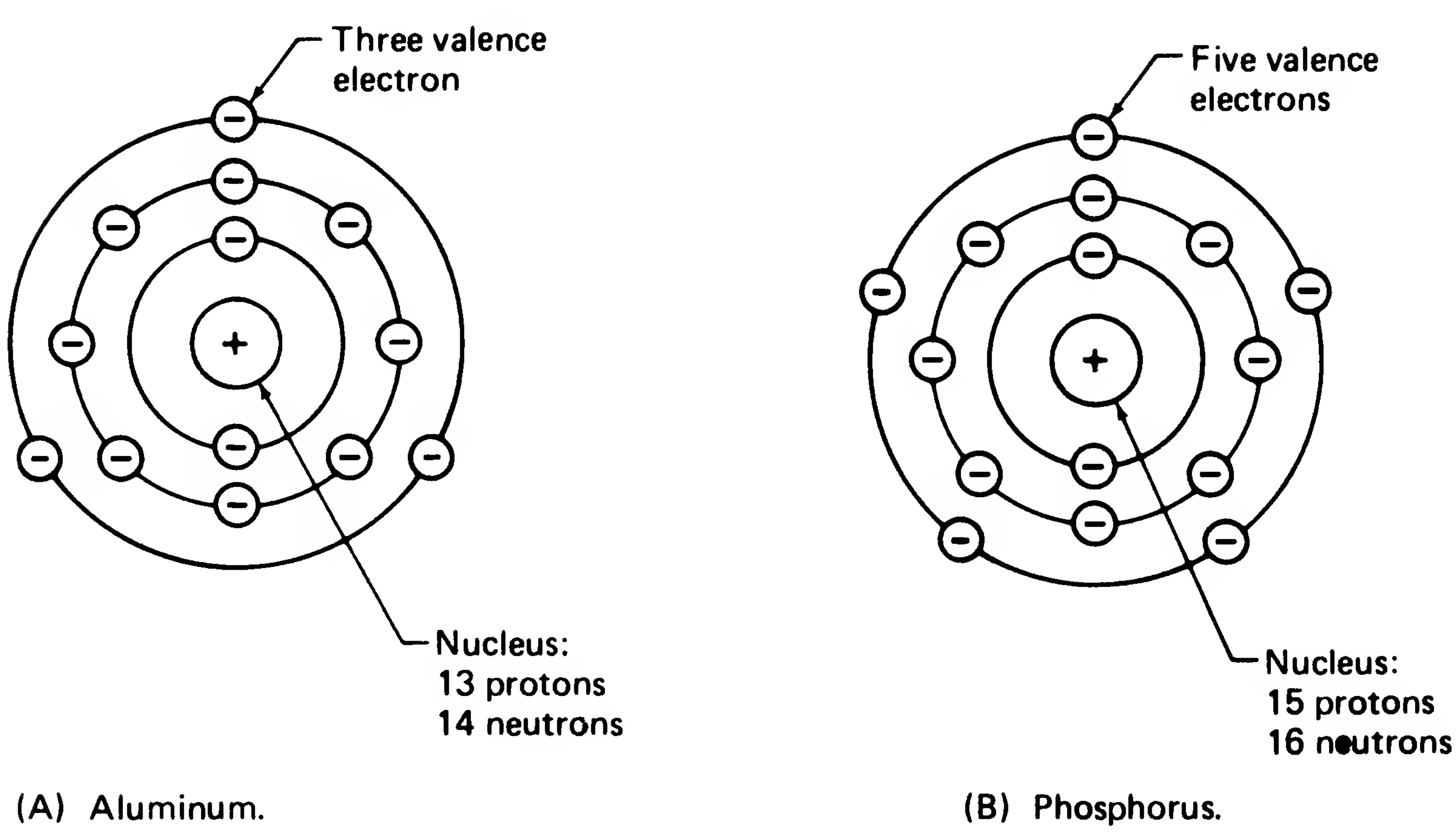


Fig. 10-2. Atoms of aluminum and phosphoros.

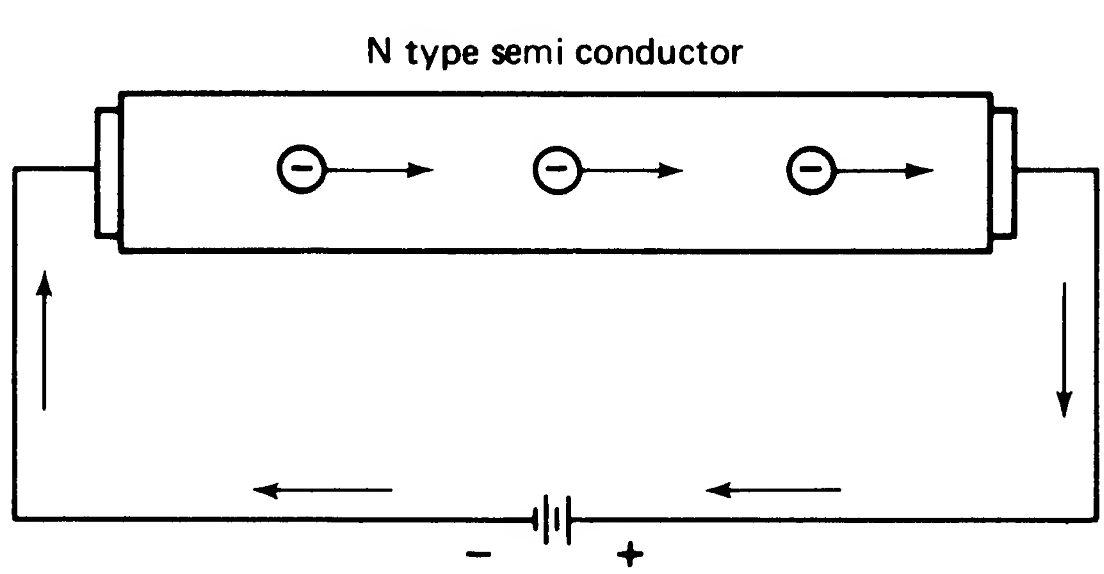


Fig. 10-3. Bohr models of aluminum and phosphorus atoms.

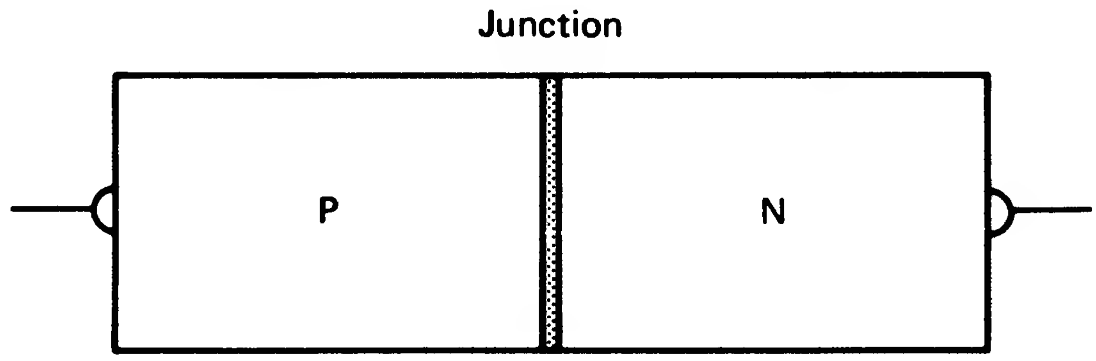


Fig. 10-4. P-N diode.

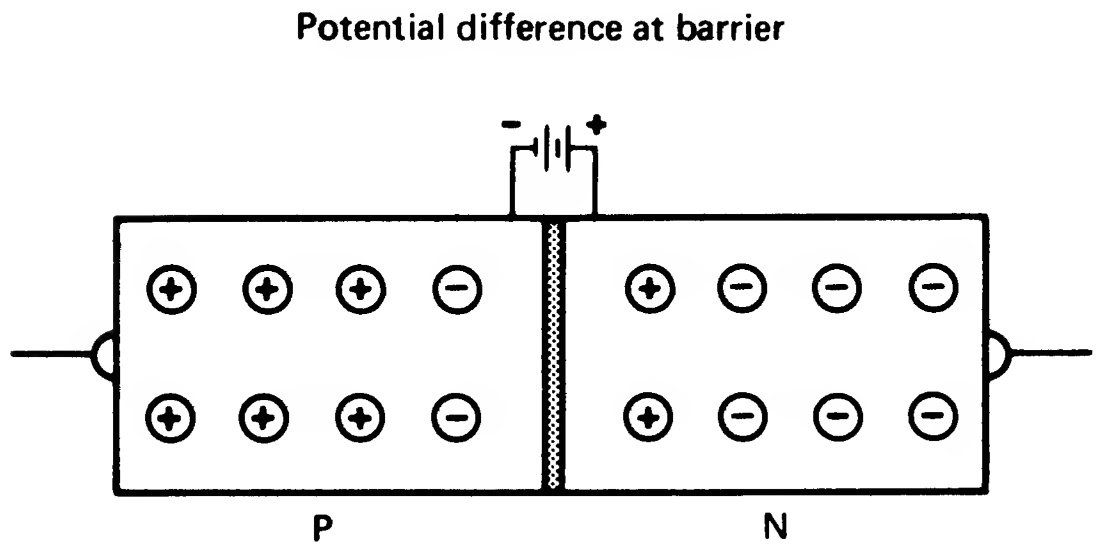


Fig. 10-5. Potential barrier at P-N junction.

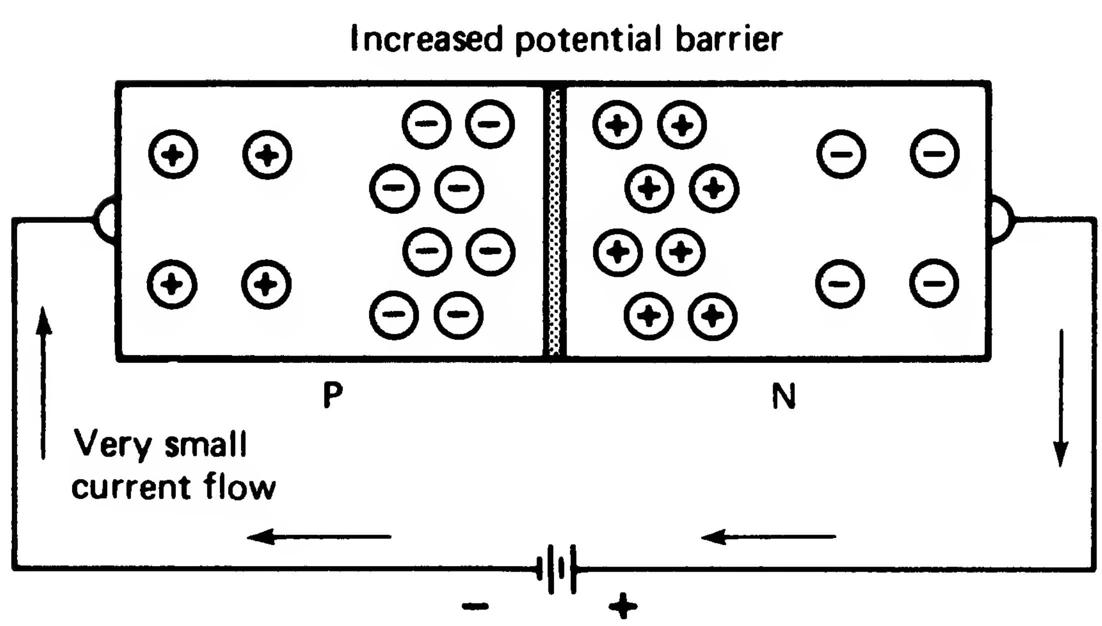


Fig. 10-6. Reverse biased P-N junction.

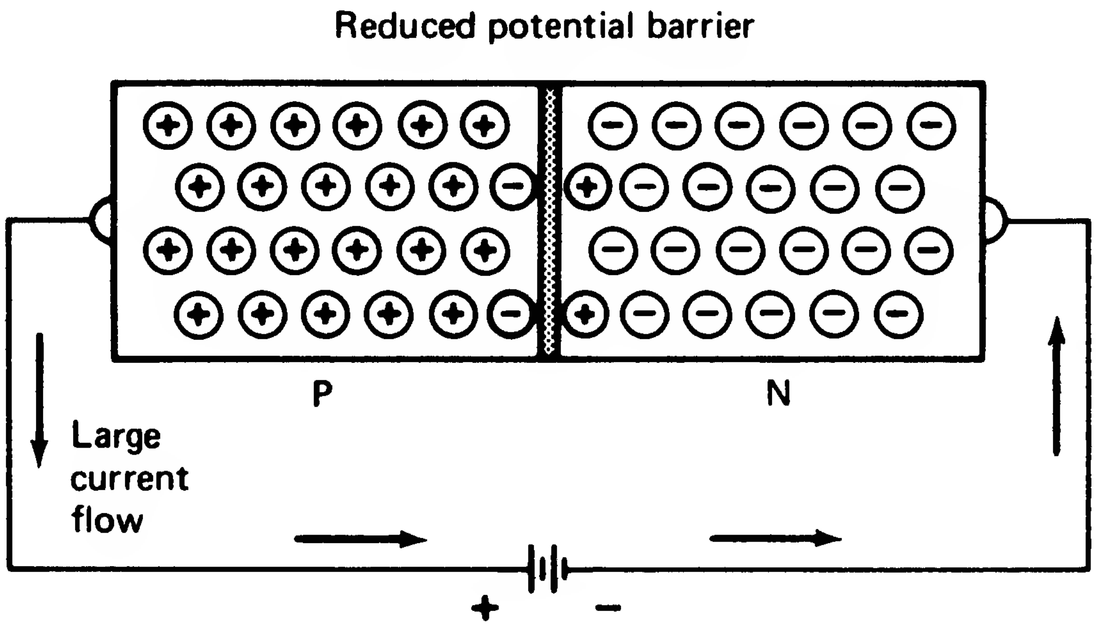


Fig. 10-7. Forward biased P-N junction.

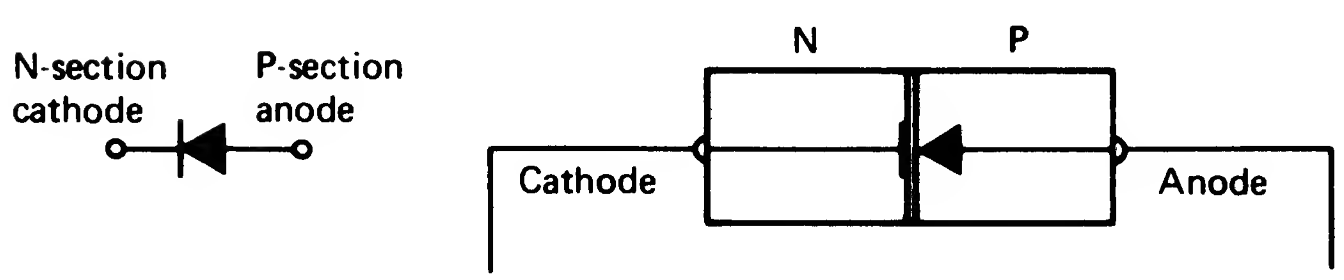


Fig. 10-8. Diode circuit symbol. Electron current flows from cathode to anode.

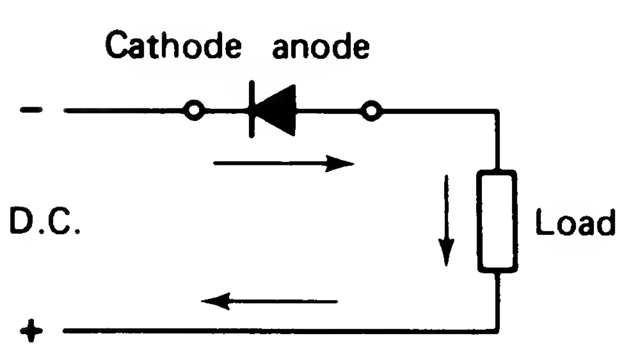
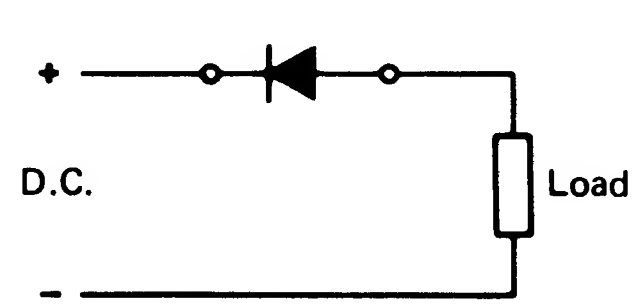


Fig. 10-9. Direction of electron current flow through diode rectifier and circuit.

Fig. 10-10. Reverse biased diode circuit. No appreciable current flow.



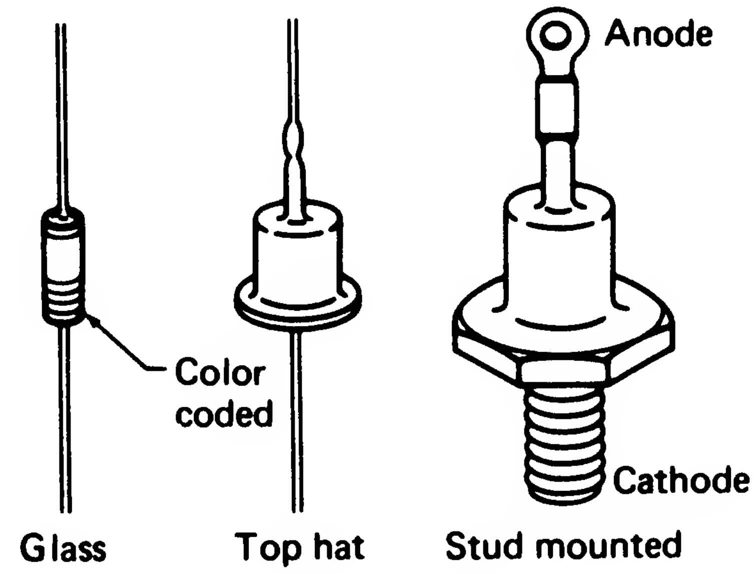


Fig. 10-11. Types of silicon diodes.

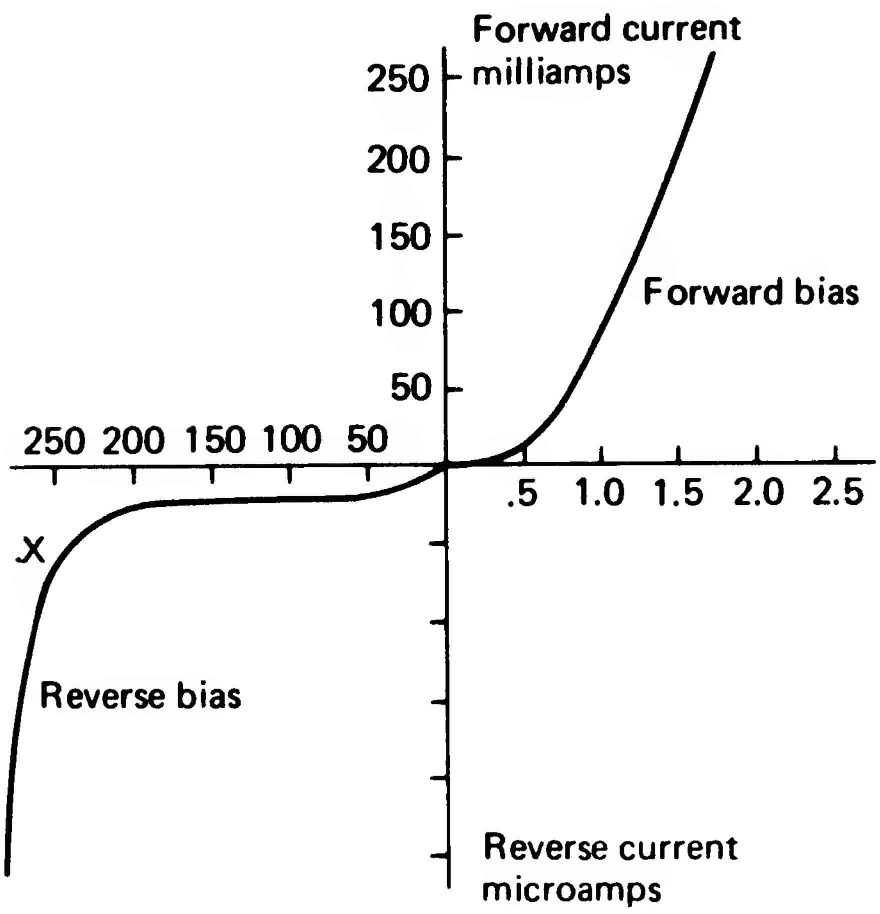


Fig. 10-12. Characteristic curve of a silicon diode.

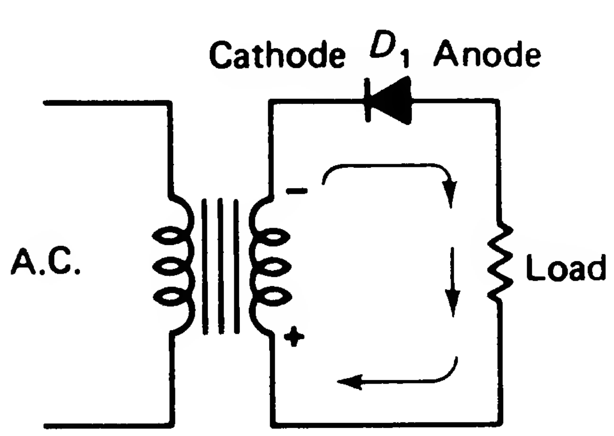


Fig. 10-13. Rectifier circuit.

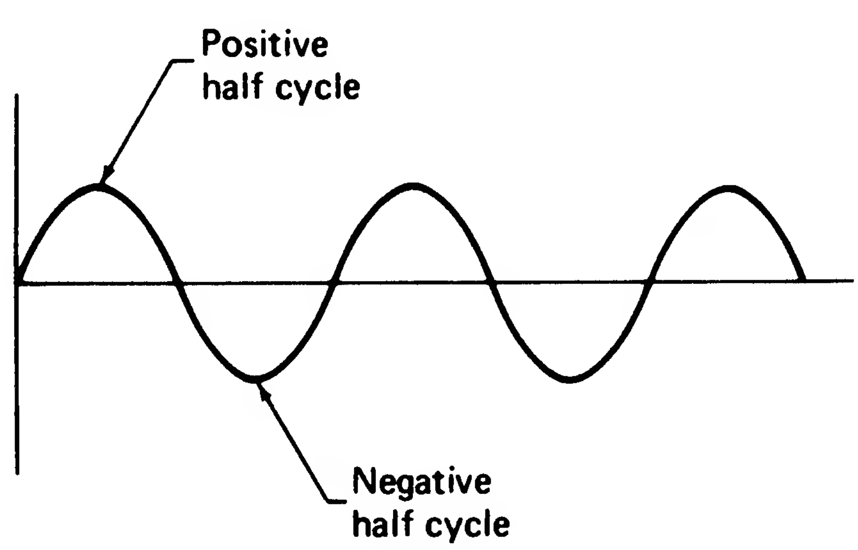


Fig. 10-14. Supply voltage or current.

Figure **10**–11; **10**–12; **10**–13; **10**–14

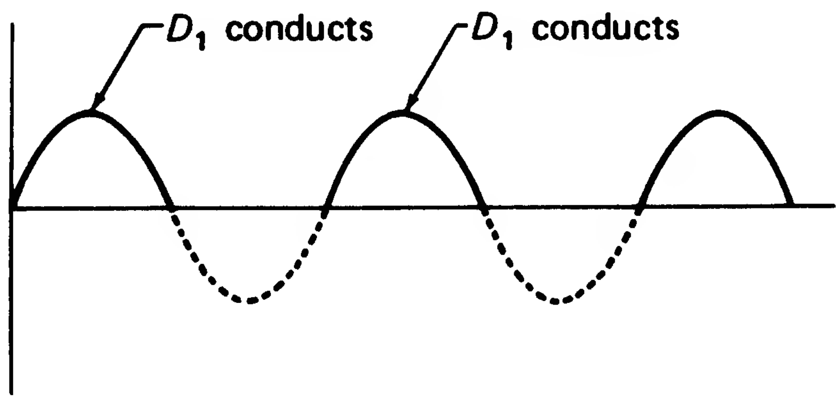


Fig. 10–15. Load voltage or current after rectification.

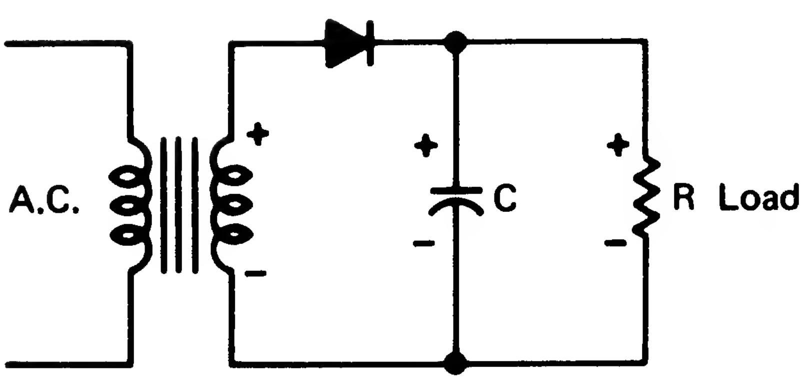


Fig. 10–16. Half-wave filtered rectification.

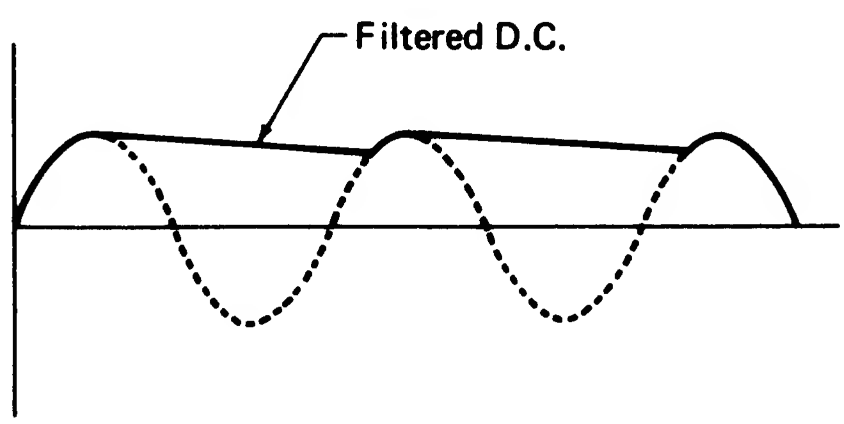
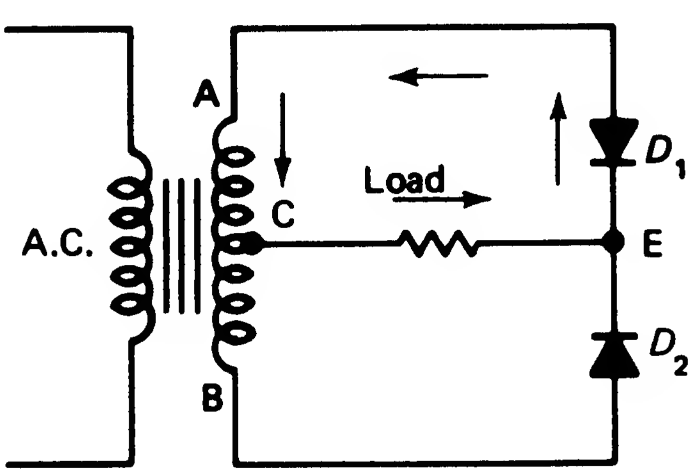


Fig. 10–17. Load voltage after filtered half-wave rectification.

Fig. 10–18. Center-tapped full-wave rectifier.



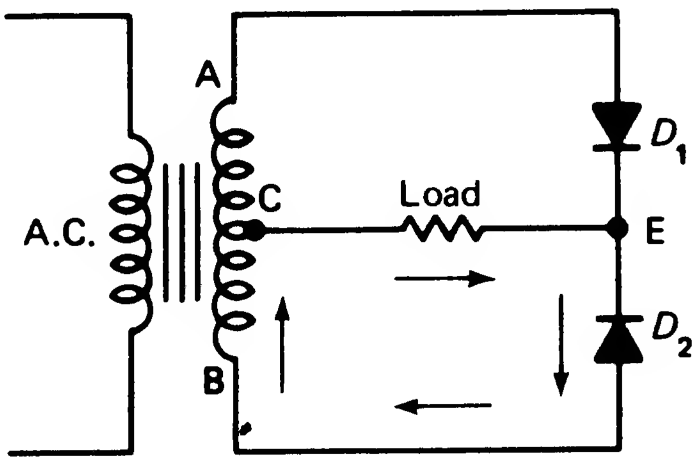


Fig. 10-19. Full-wave rectification. B is positive in respect to C.

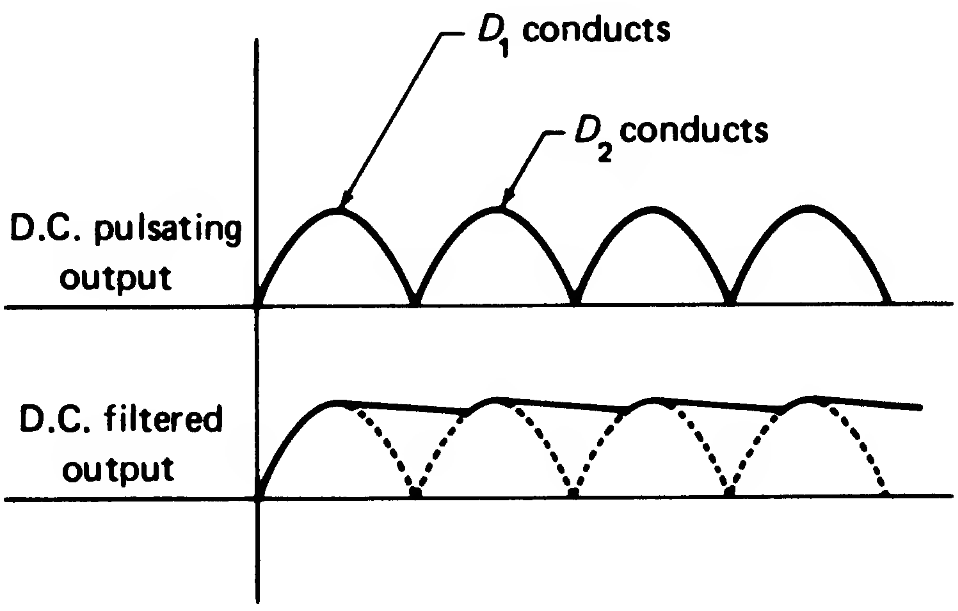


Fig. 10-20. Load voltage of a full-wave rectifier. A unfiltered, B filtered.

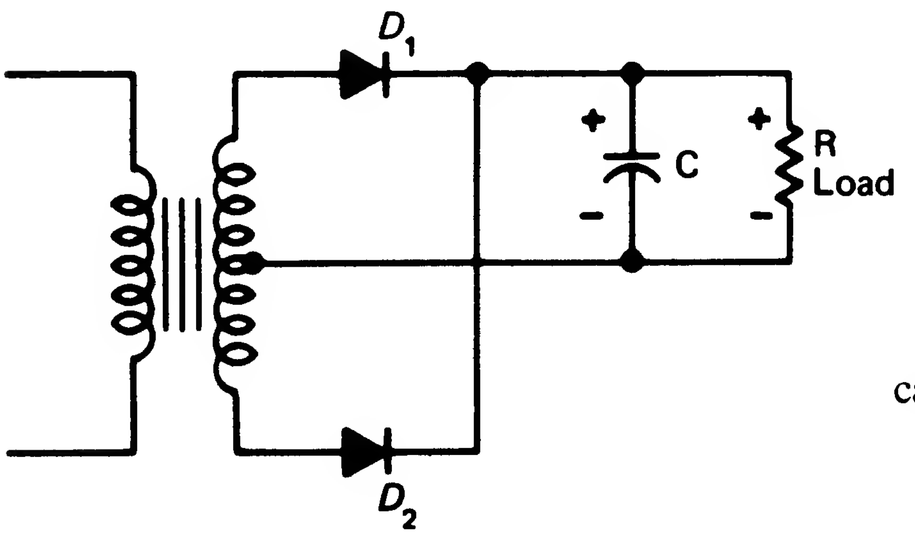


Fig. 10-21. Full-wave filtered rectification.

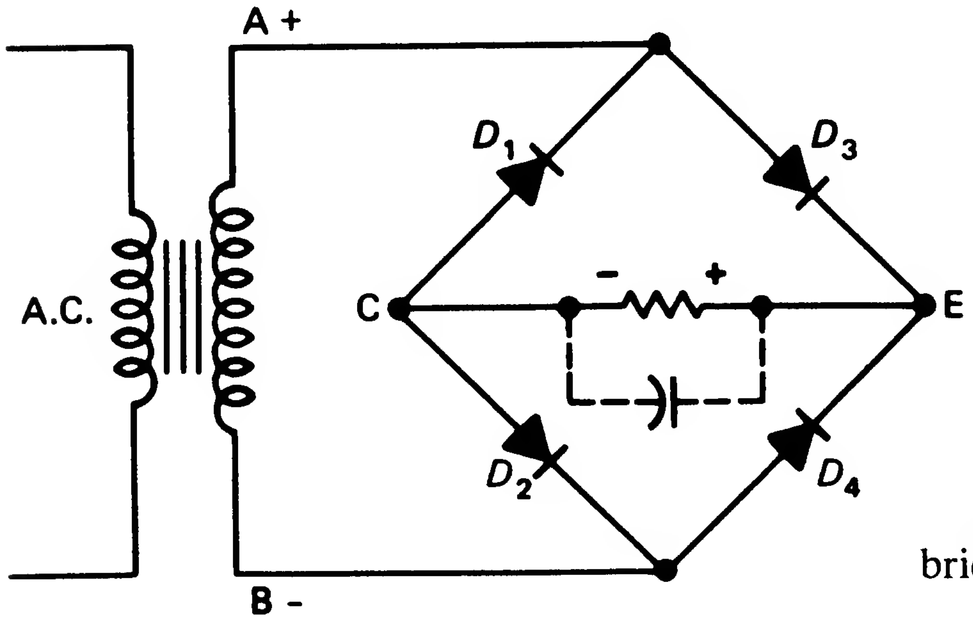


Fig. 10-22a,b. Filtered full-wave bridge rectification.

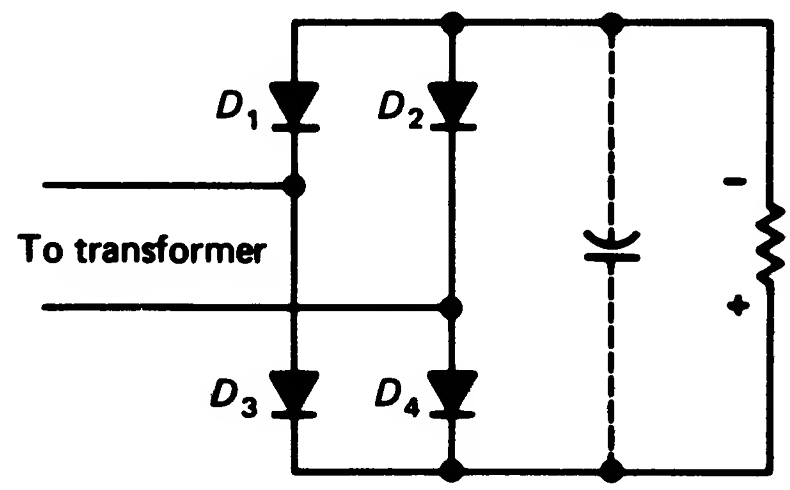


Fig. 10-22 (*continued*).

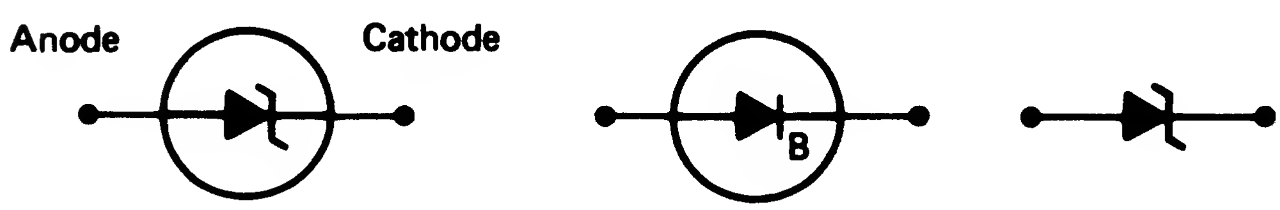


Fig. 10-23. Circuit symbol of a Zener diode.

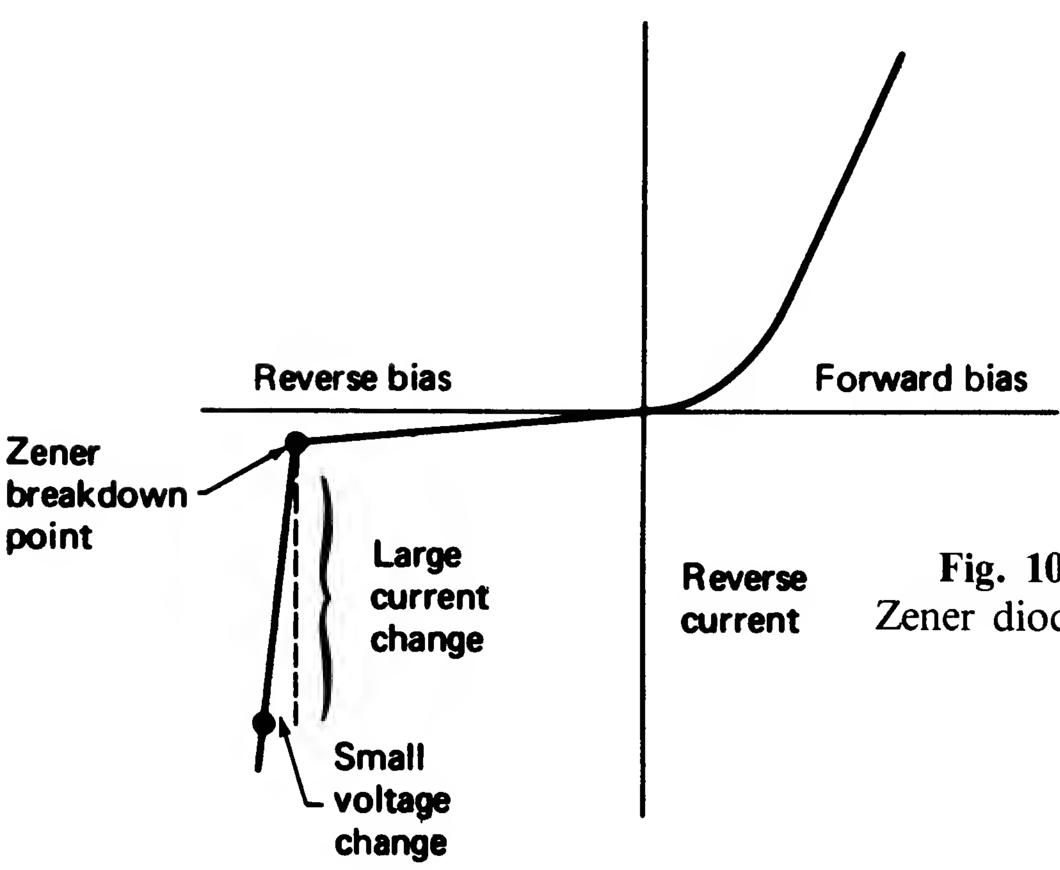


Fig. 10-24. Characteristic curve of a Zener diode.

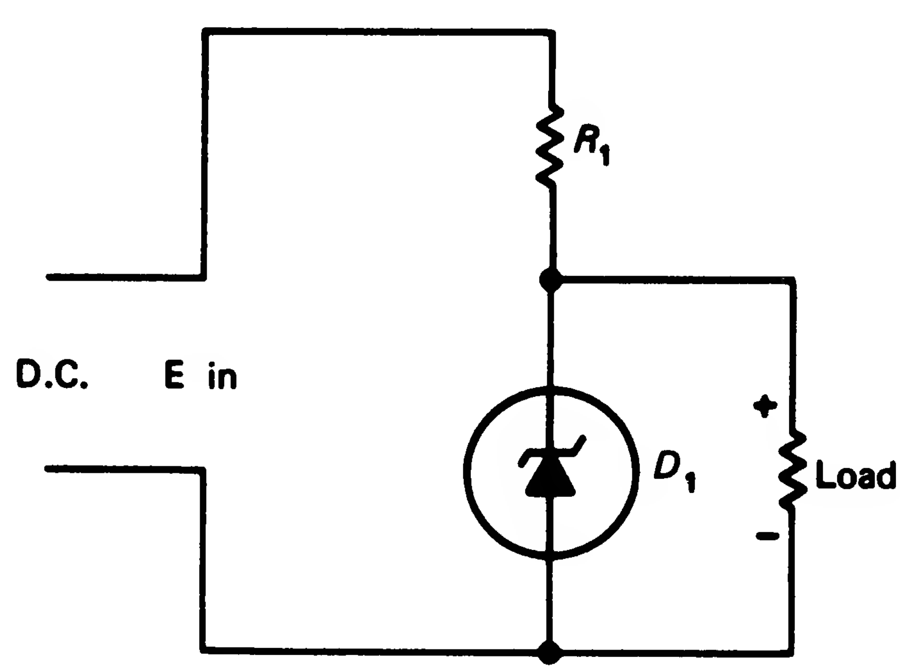


Fig. 10-25. Zenor voltage regulator.

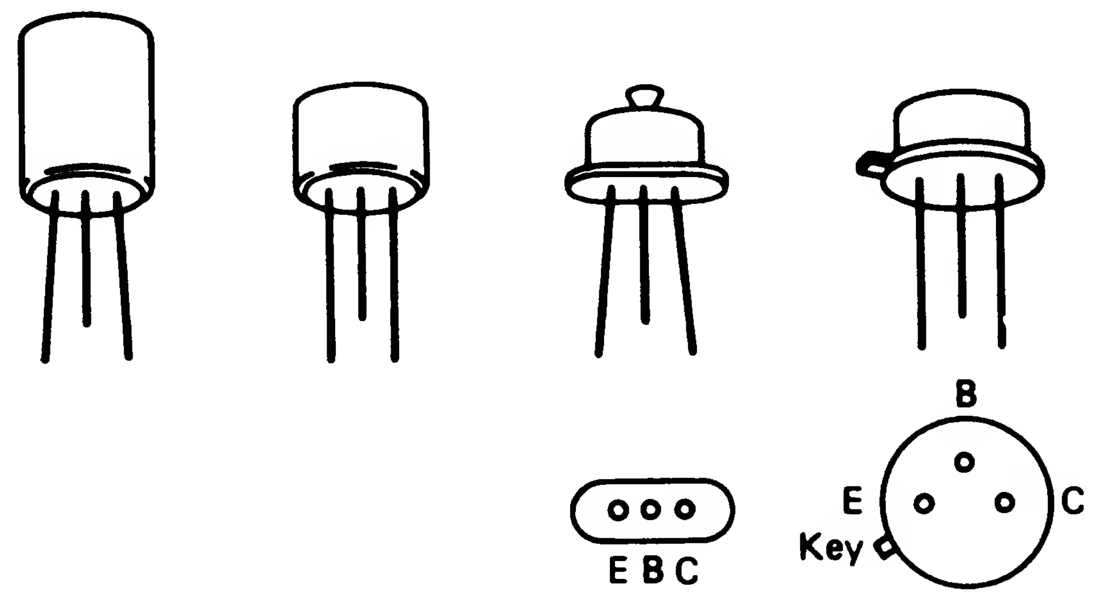


Fig. 10–26. Typical transistor cases.

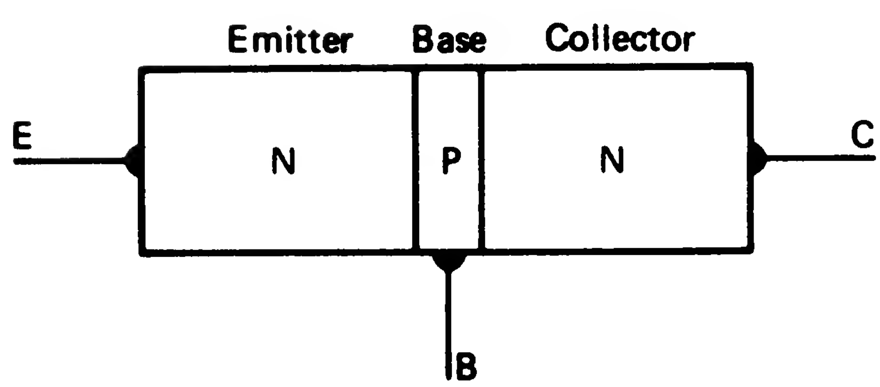


Fig. 10–27. NPN transistor structure.

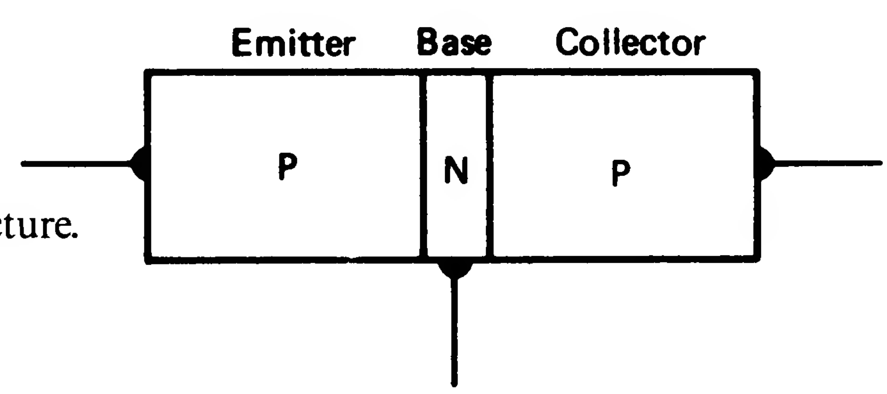


Fig. 10–28. PNP transistor structure.

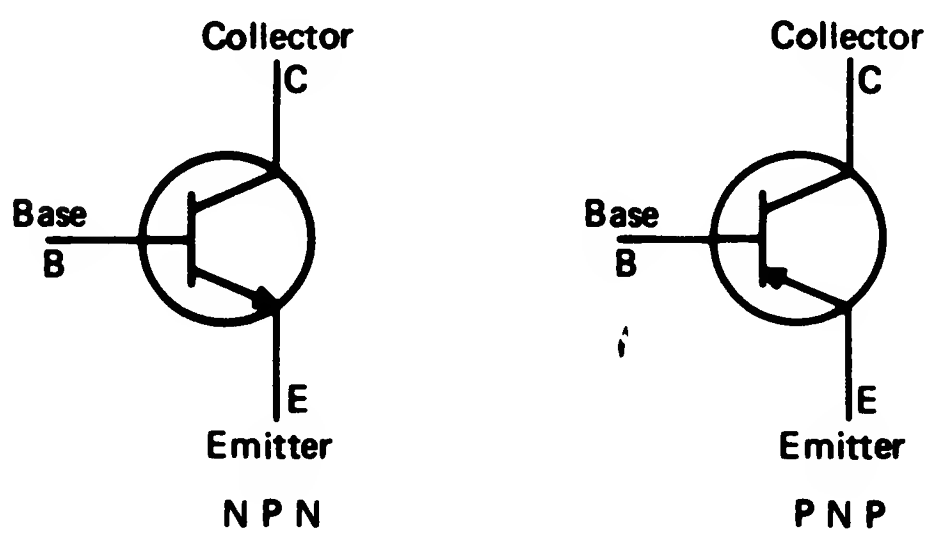


Fig. 10–29. Circuit symbols of transistors.

Figures **10–26**; **10–27**; **10–28**; **10–29**

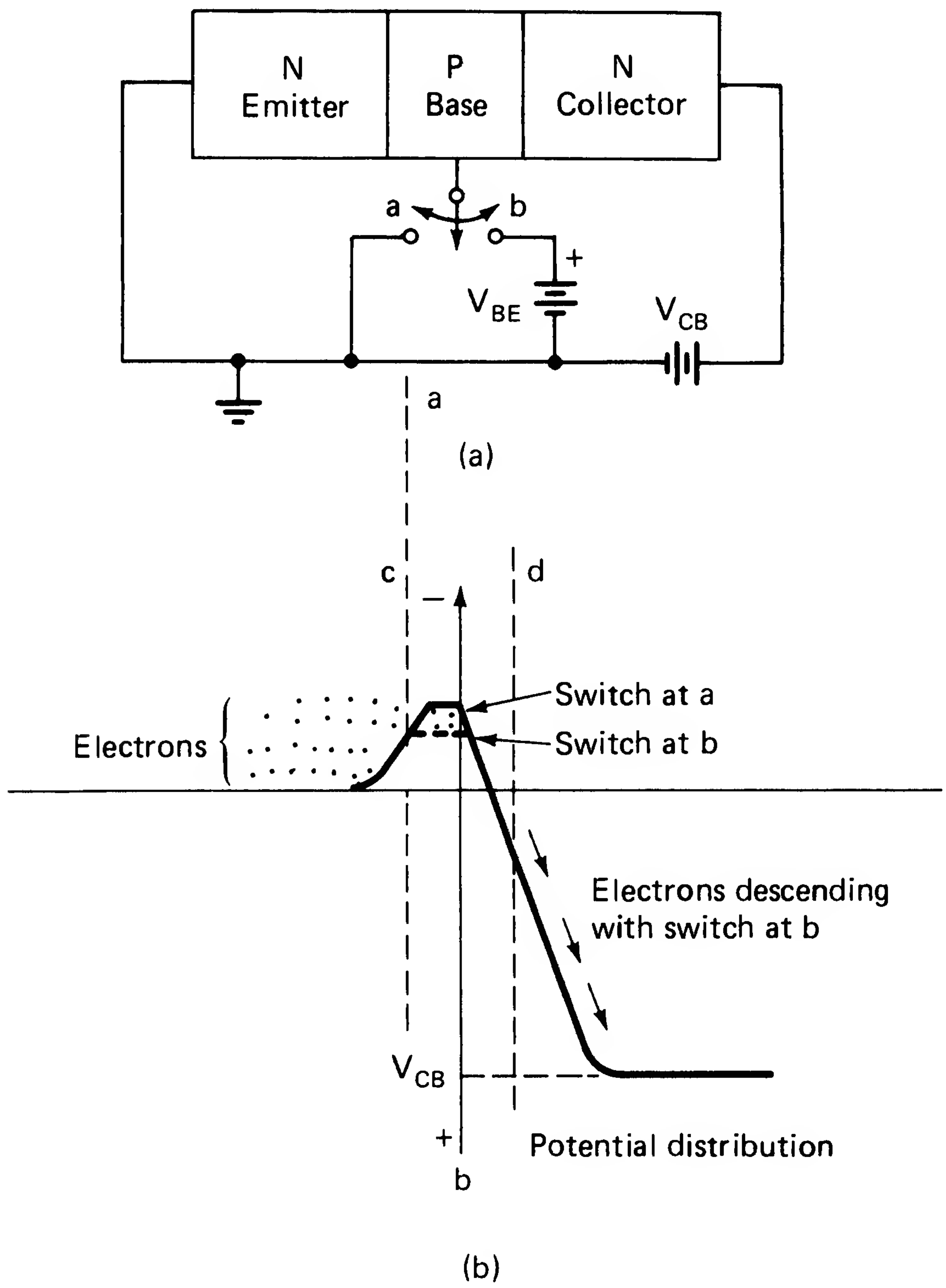


Fig. 10-30. Amplification in the NPN transistor. (a) Transistor structure. (b) potential distribution. *(Rosenstein, Morris, Modern Electronic Devices: Circuit Design and Application, A Reston Publication, reprinted by permission of Prentice-Hall.)*

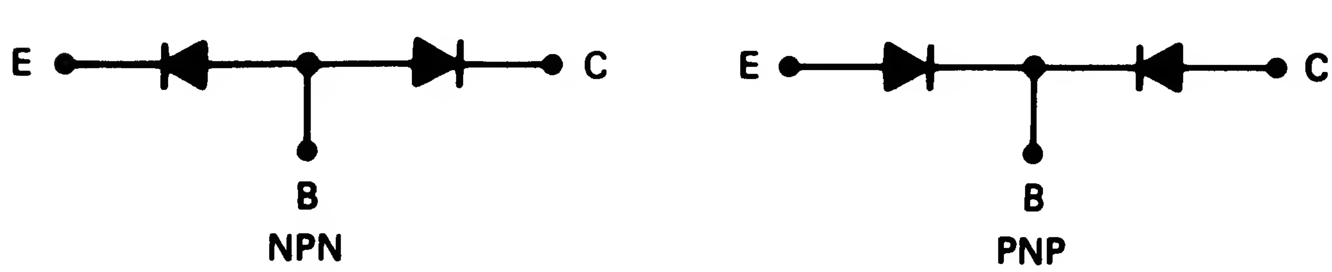


Fig. 10-31. Transistor model using 2 diodes.

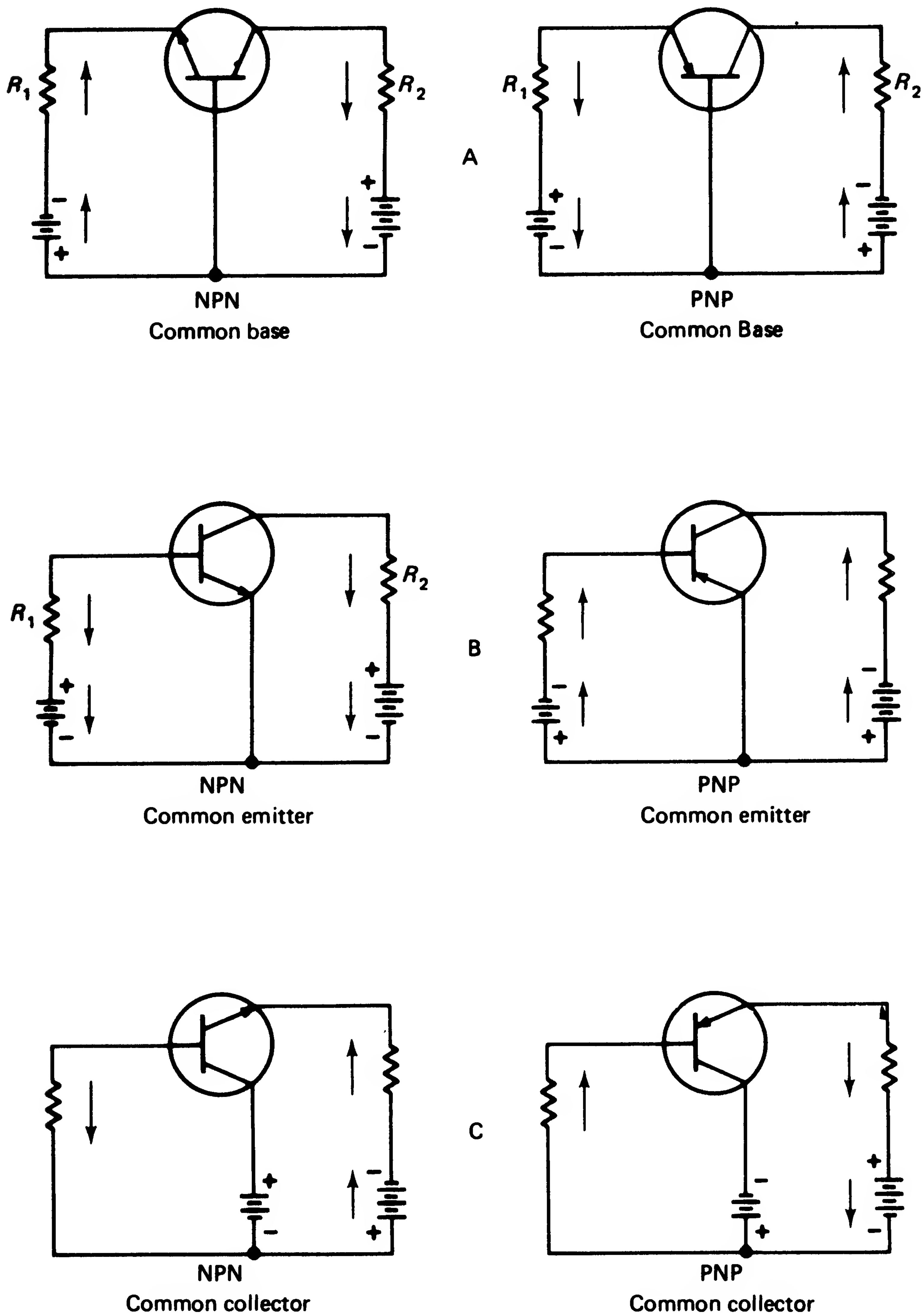


Fig. 10–32. Transistor circuit configurations.

Figure **10**–32

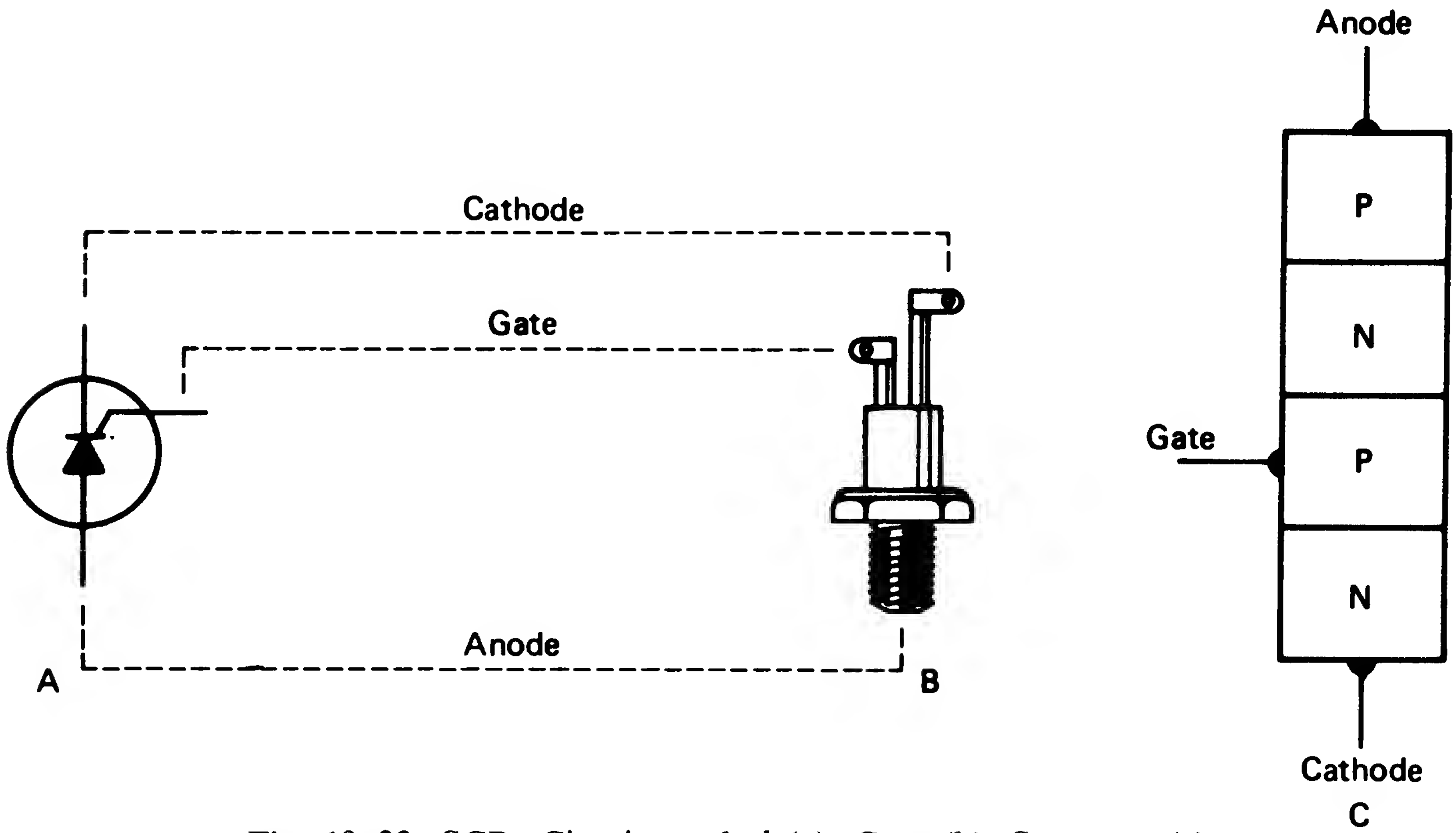


Fig. 10-33. SCR. Circuit symbol (a). Case (b). Structure (c).

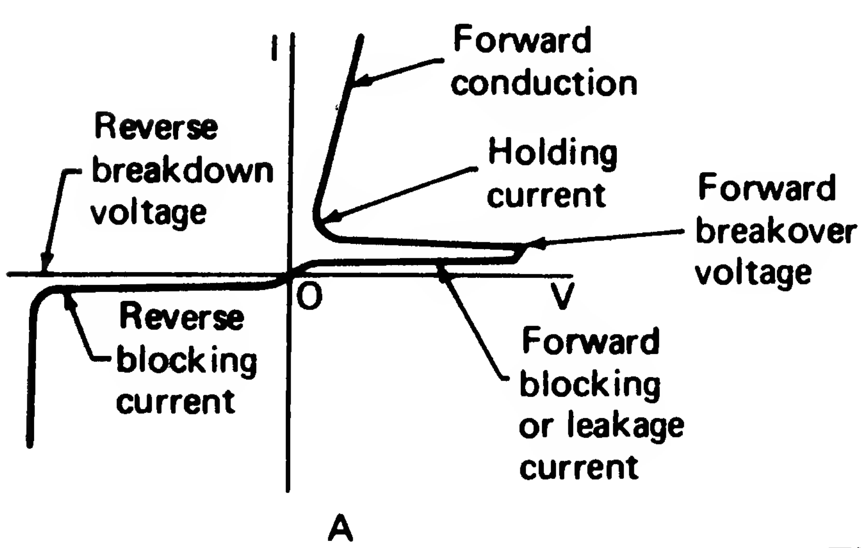


Fig. 10-34a. SCR characteristics.

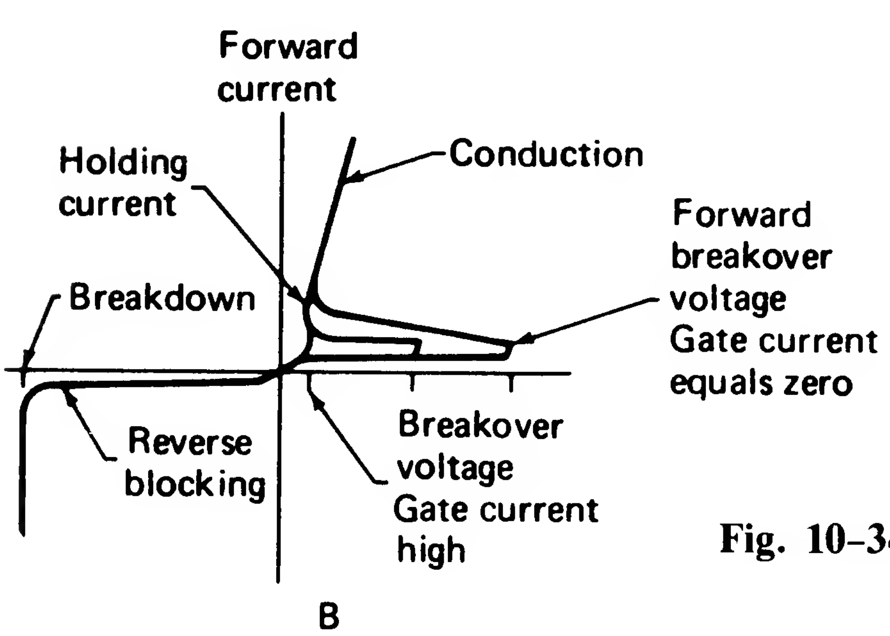


Fig. 10-34b. Gate current-O/V.

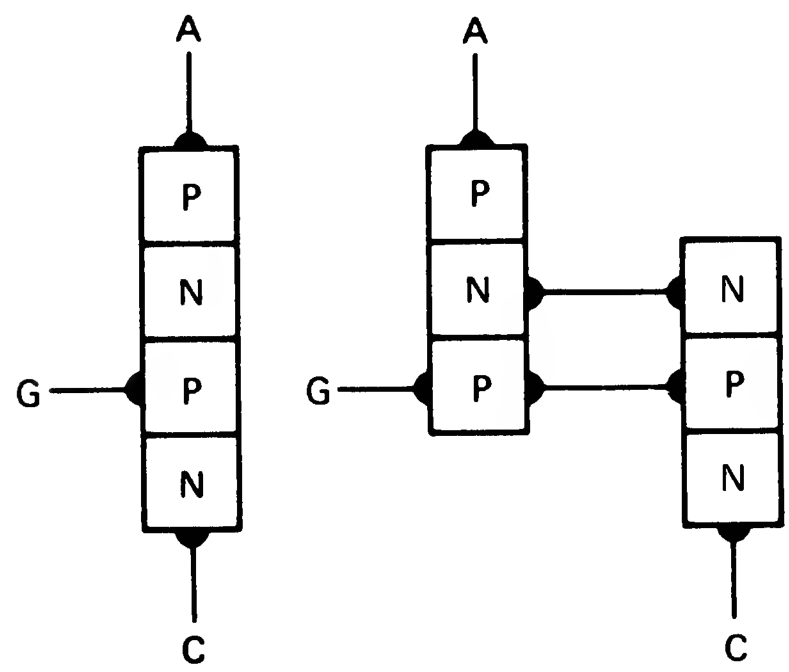


Fig. 10–35. Transistor model of SCR.

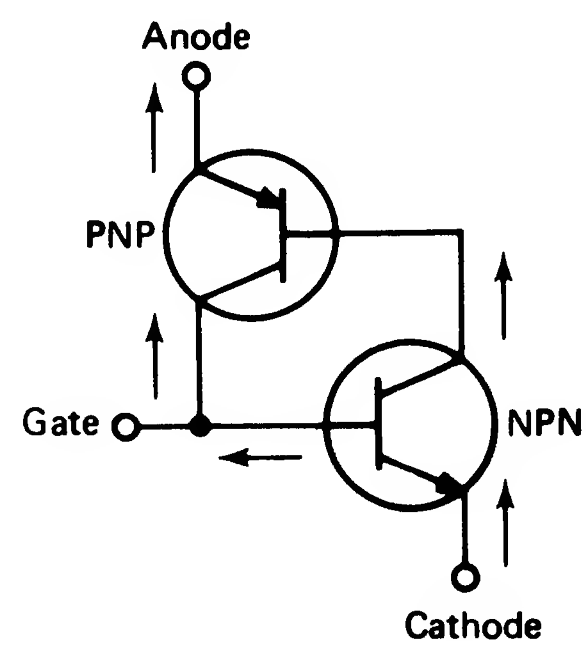


Fig. 10–36. SCR operation.

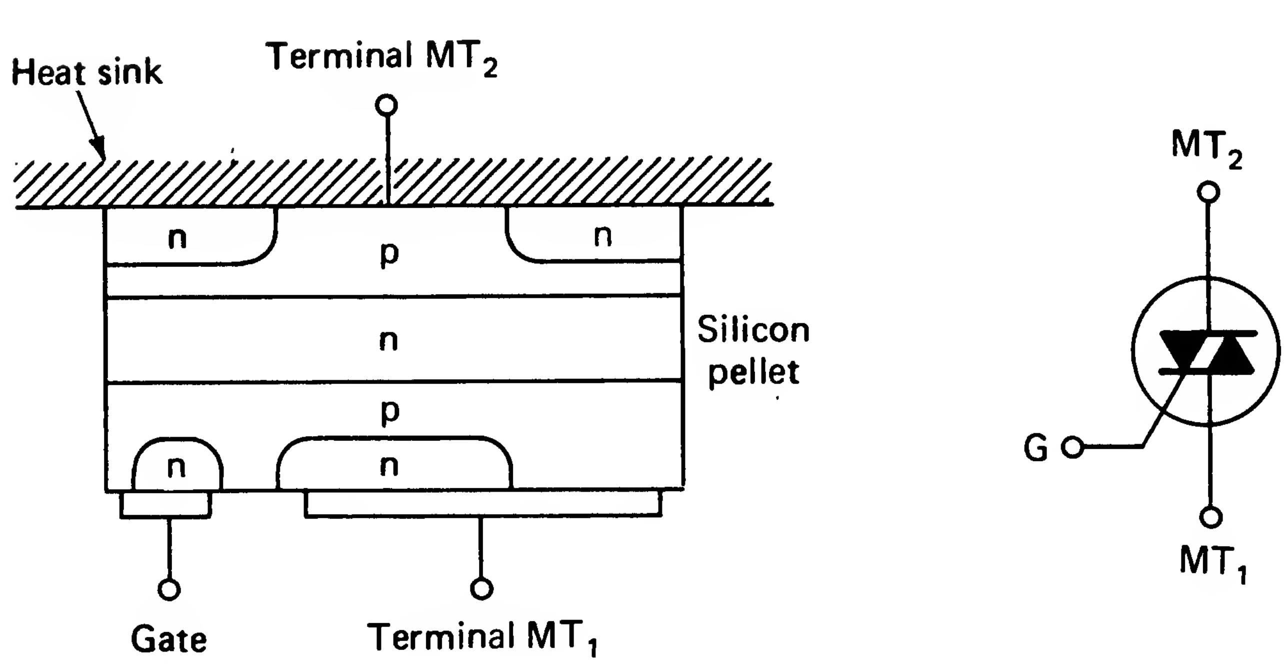


Fig. 10–37. The triac. Simplified pellet structure (a). Circuit symbol (b). *(General Electric Co., Semiconductor Products Dept.)*

Figures **10–35**; **10–36**; **10–37**

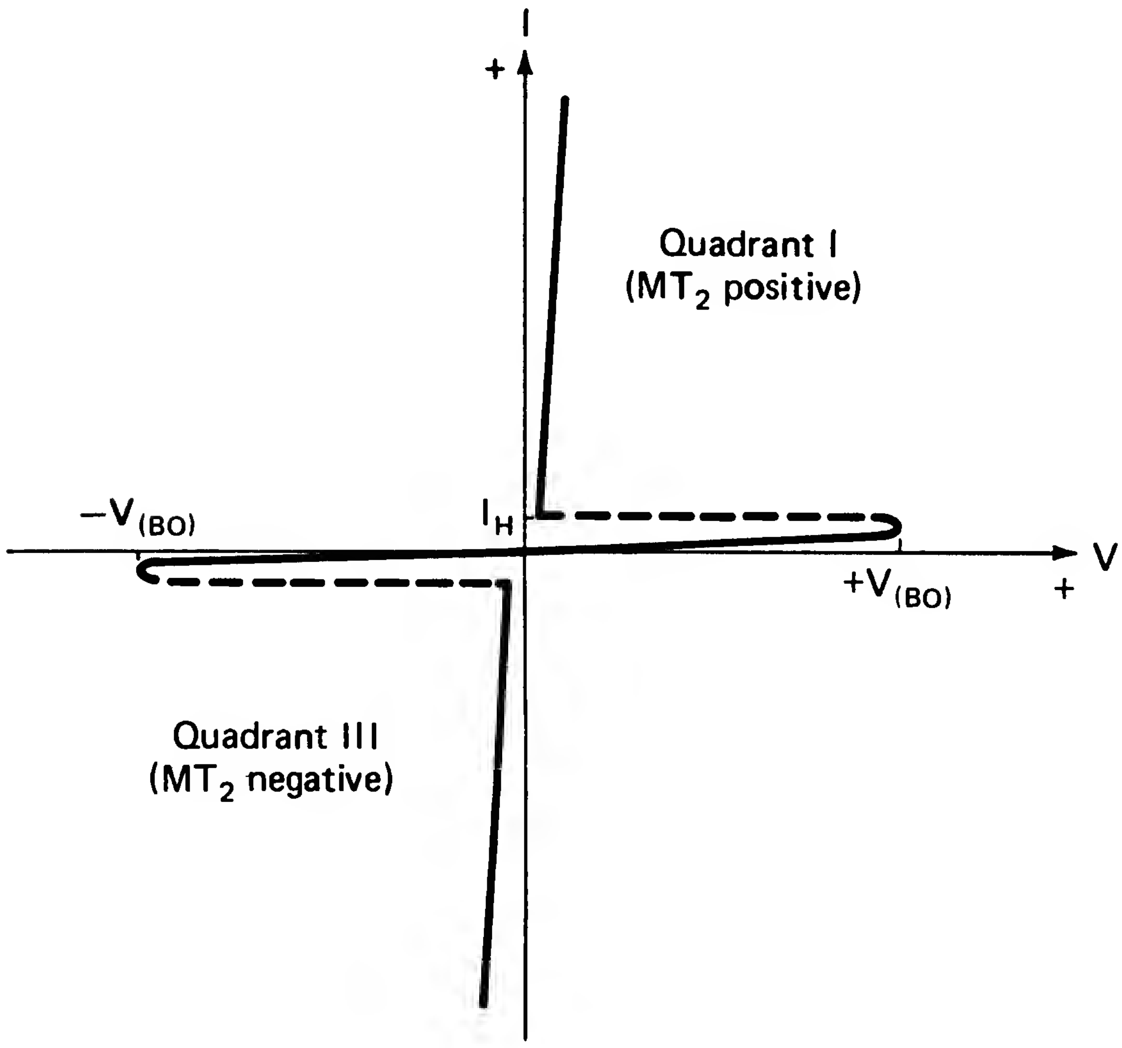


Fig. 10-38. Ac characteristics of the triac. *(General Electric Co., Semiconductor Products Dept.)*

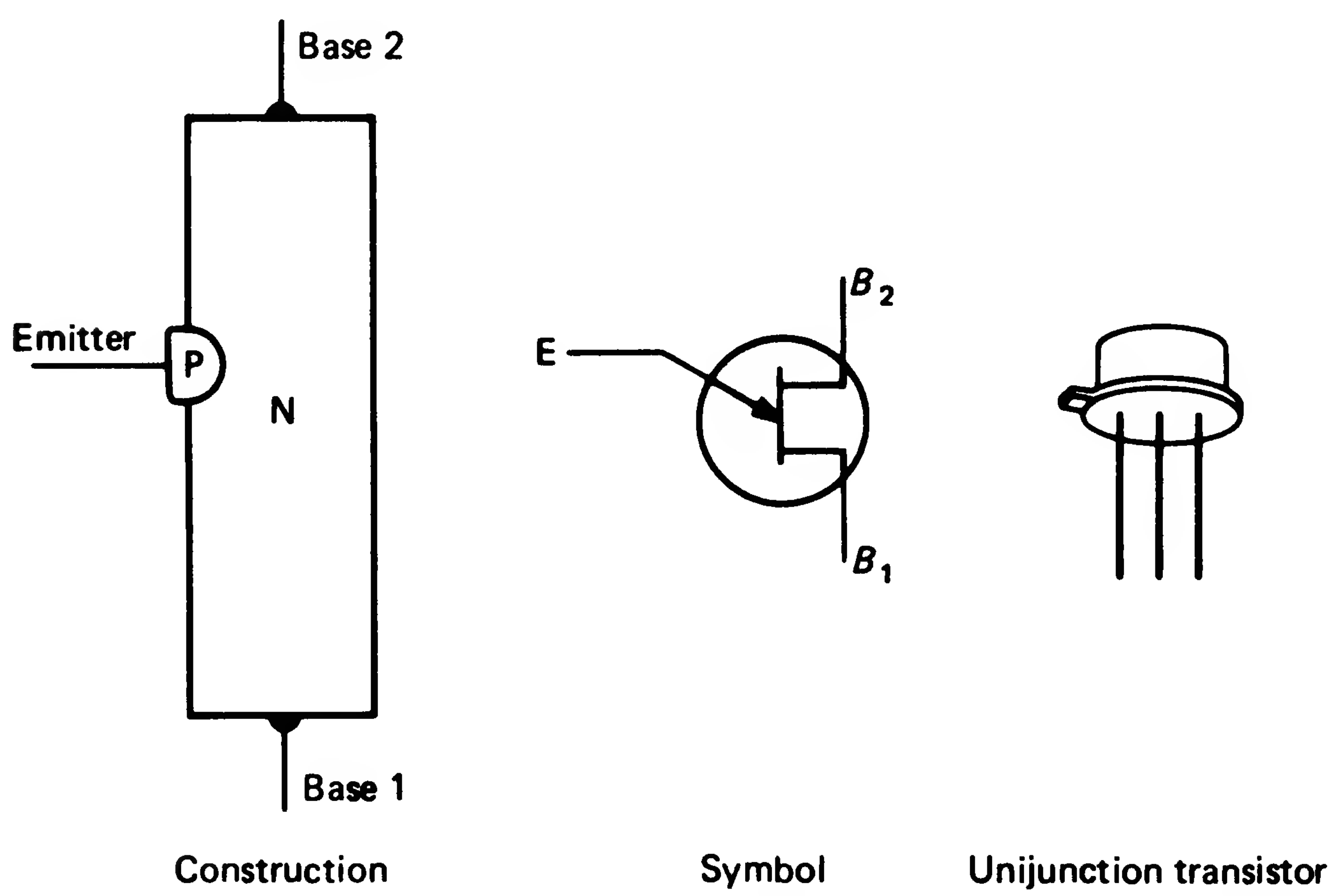


Fig. 10-39. Structure, circuit symbol and case of the unijunction transistor.

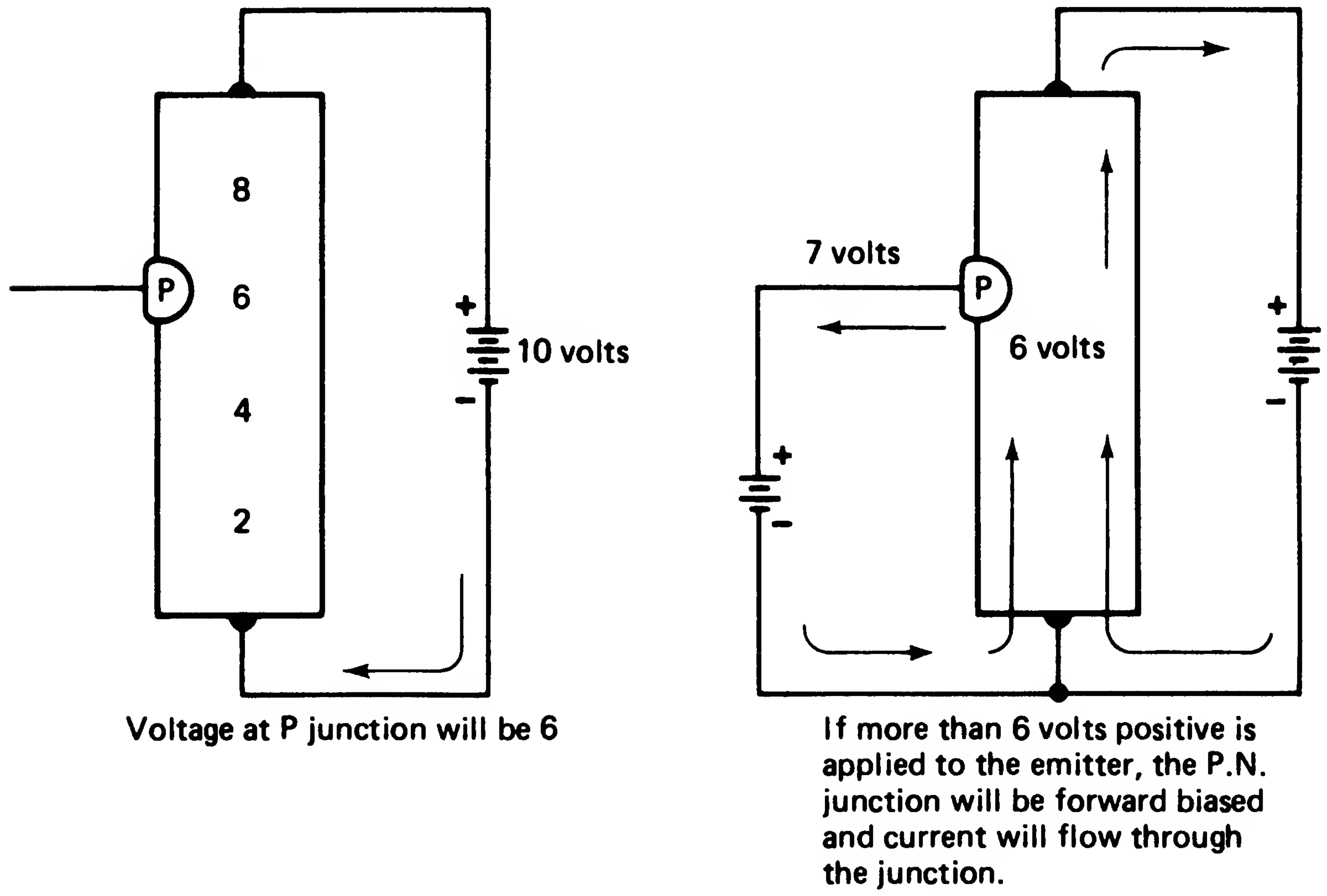


Fig. 10-40. Voltage division in the UJT.

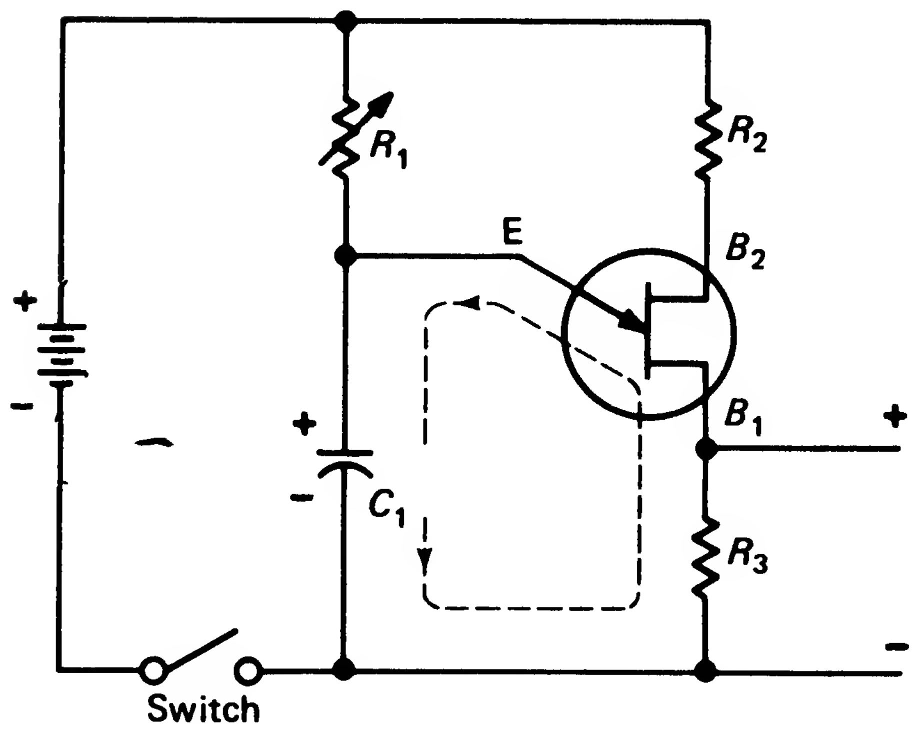


Fig. 10-41. UJT relaxation oscillator circuit.

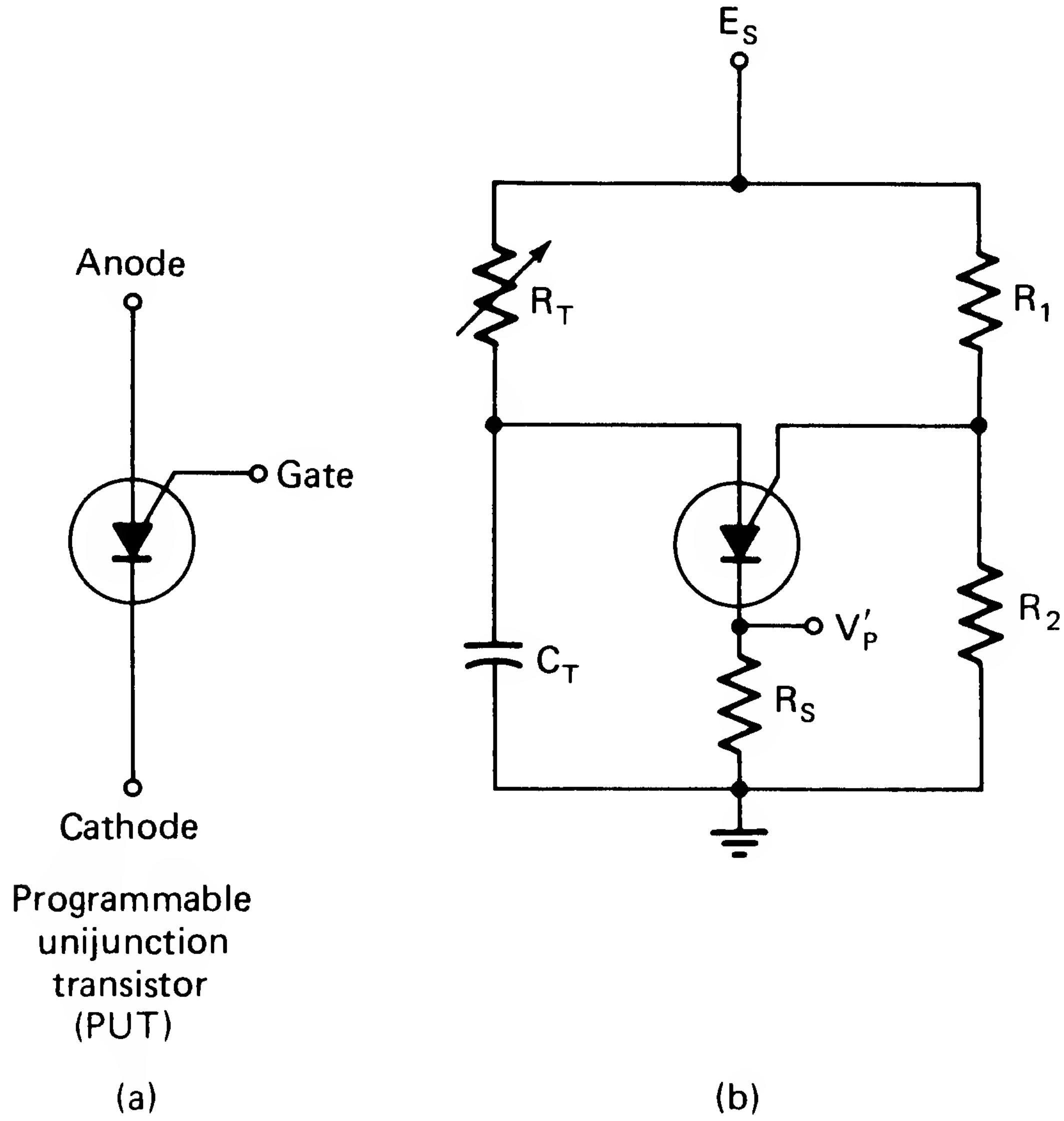


Fig. 10-42. PUT circuit symbol and relaxation oscillator.

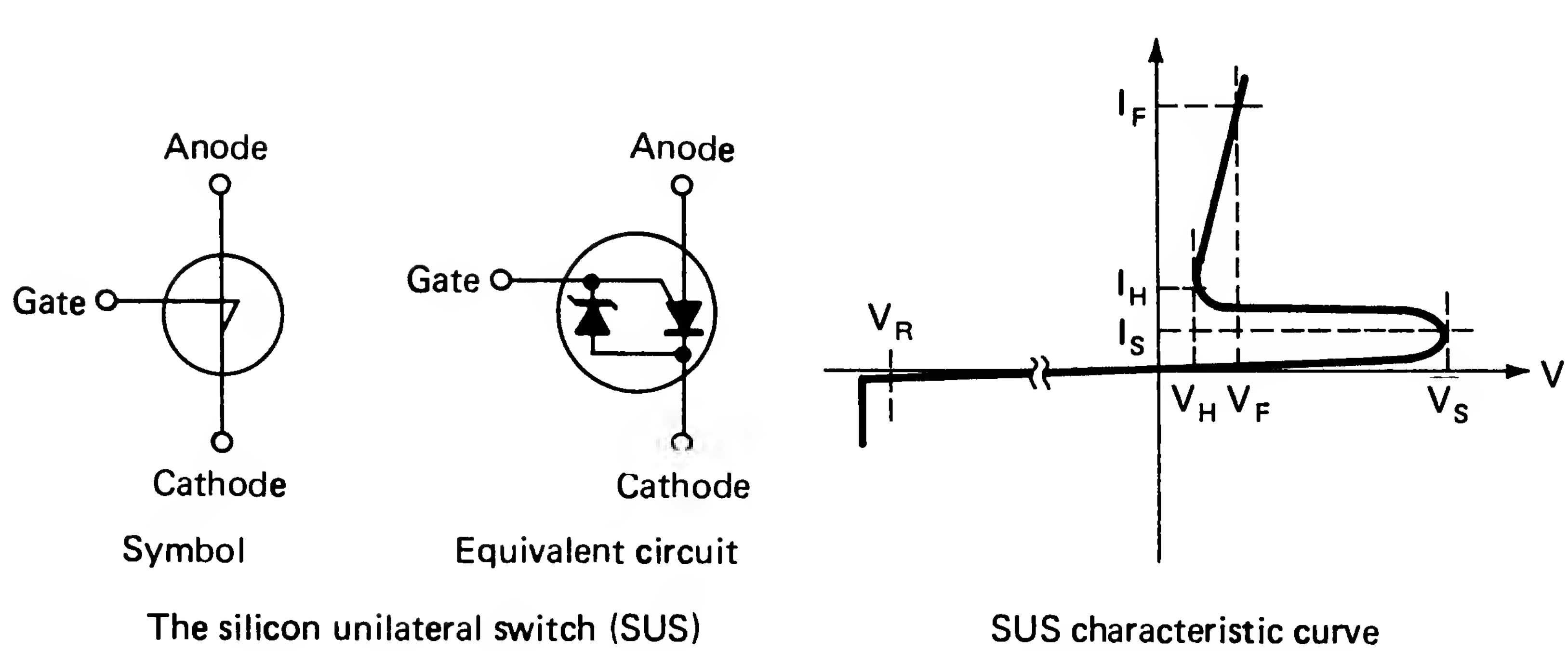


Fig. 10-43. The silicon unilateral switch.

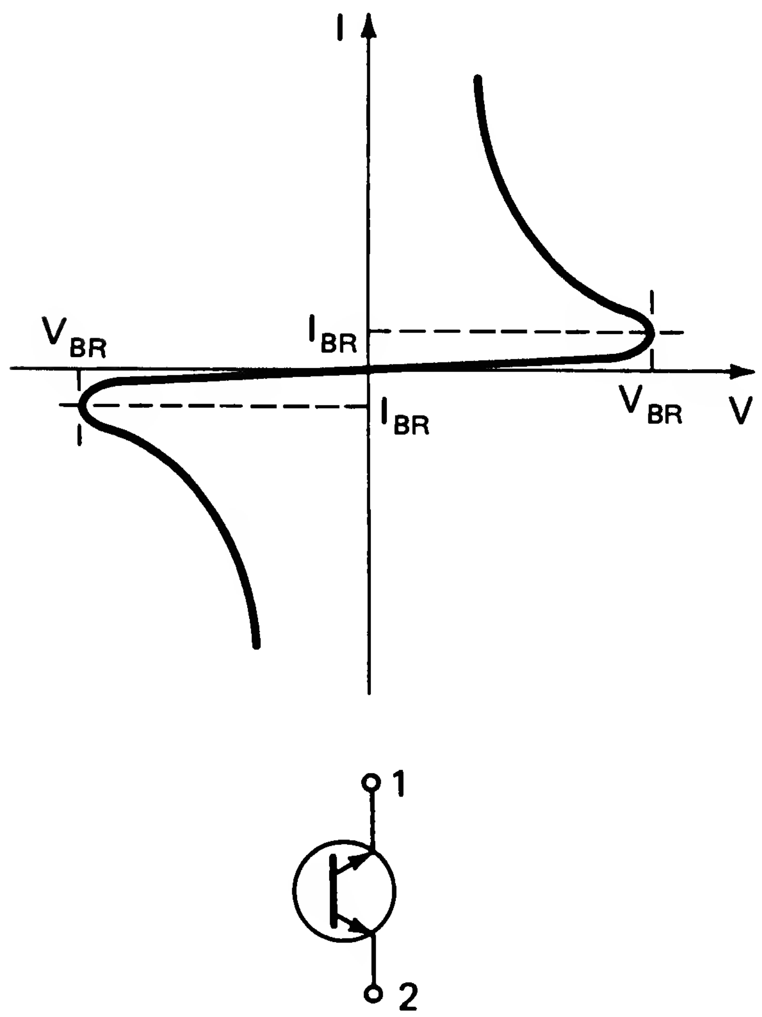


Fig. 10-44. The diac.

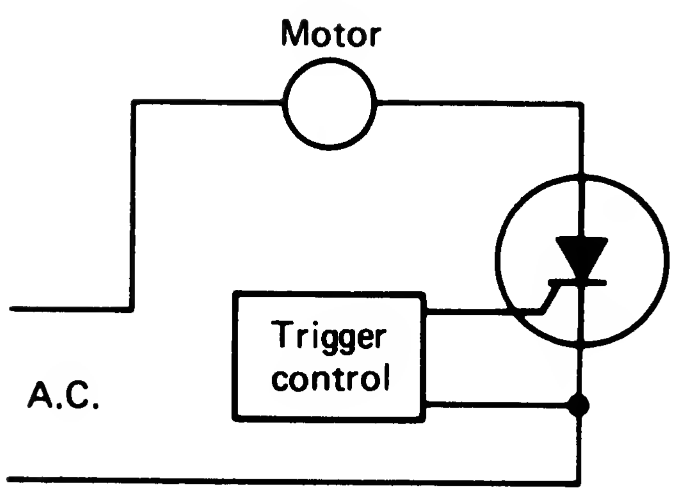


Fig. 10-45. Half-wave phase control circuit.

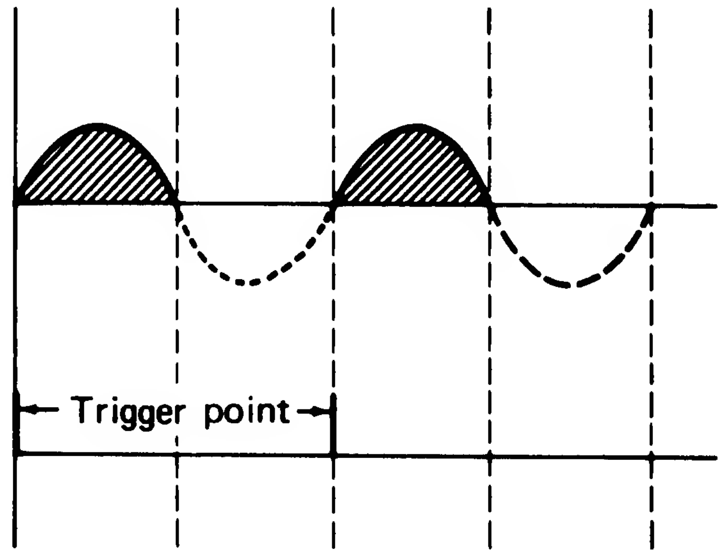


Fig. 10-46. Power delivered when SCR fires at 0°.

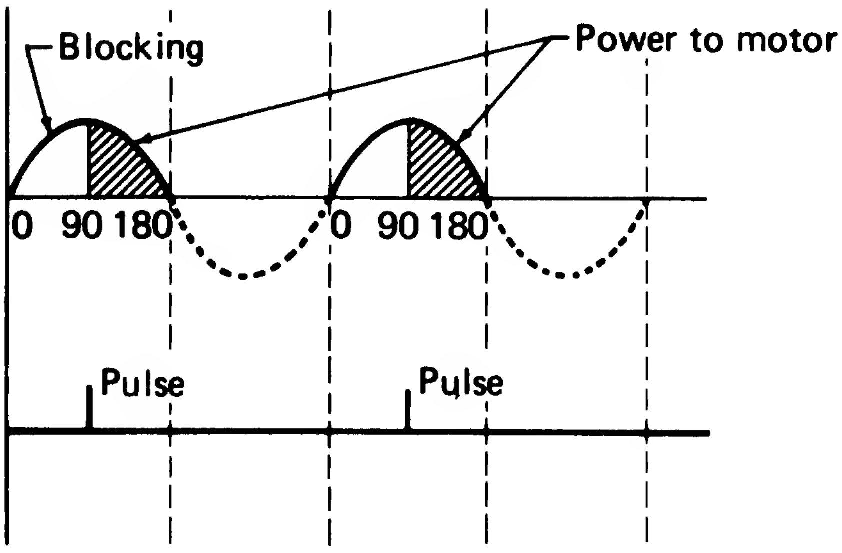


Fig. 10-47. Power delivered by **Fig. 10-4c** when SCR fires at 90°.

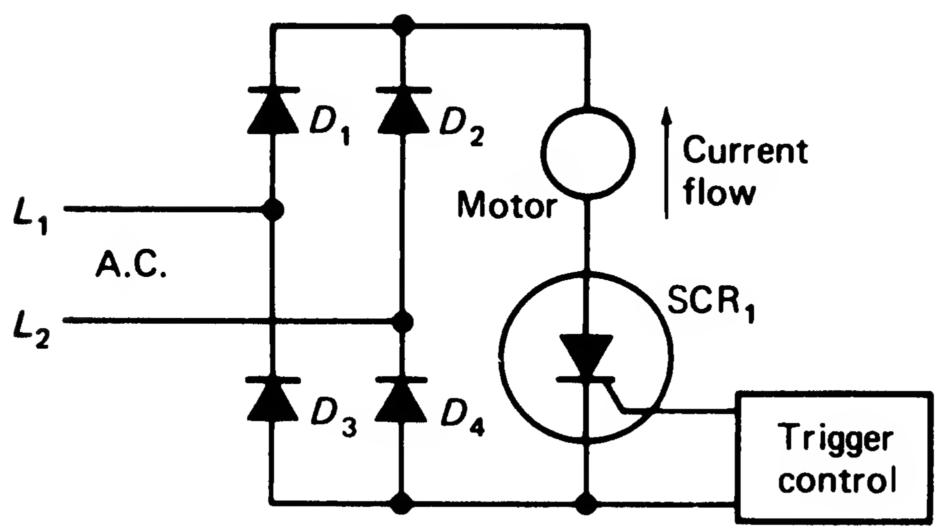


Fig. 10-48. Full-wave dc phase control.

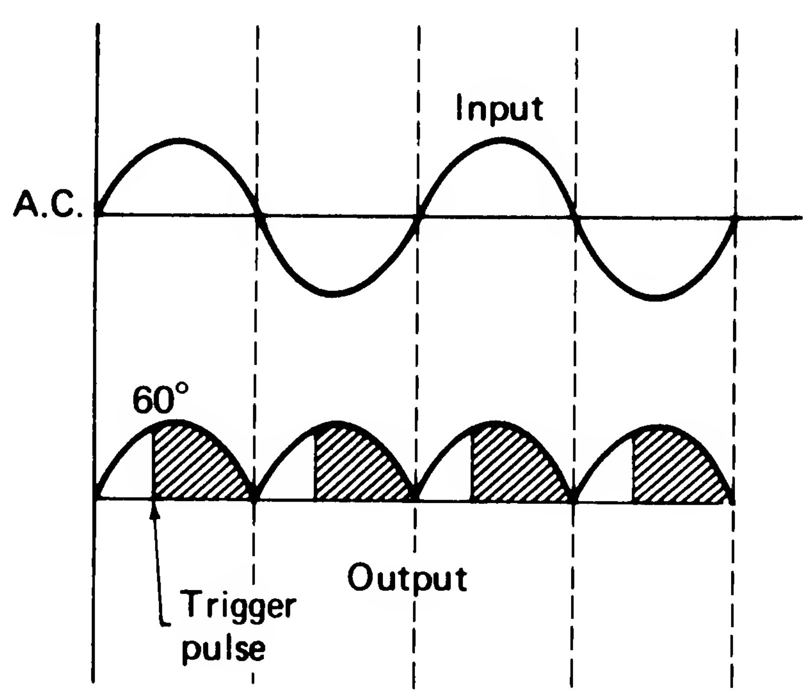
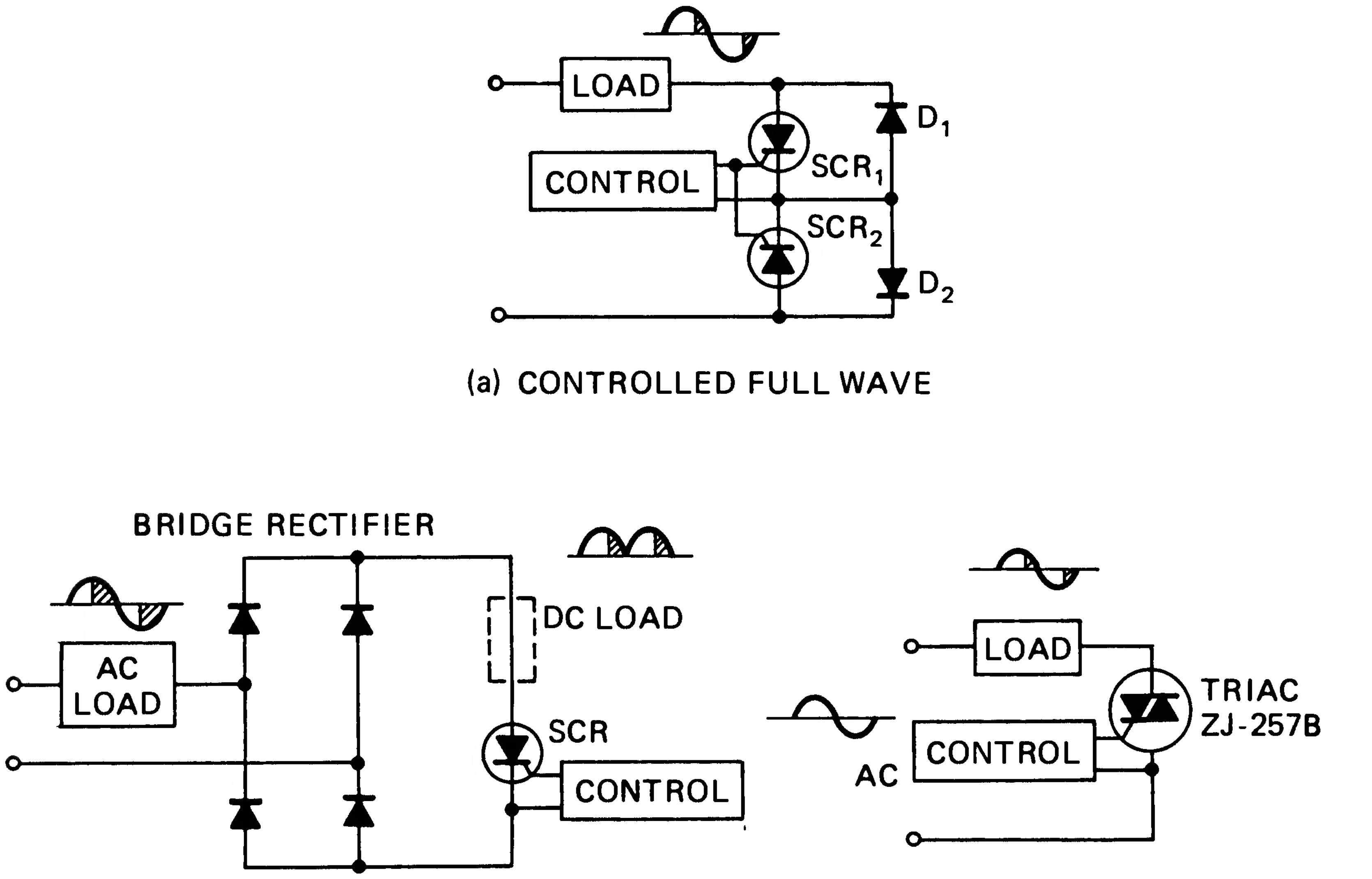


Fig. 10-49. Power delivered by **Fig. 10-48** when SCR fires at 60°.

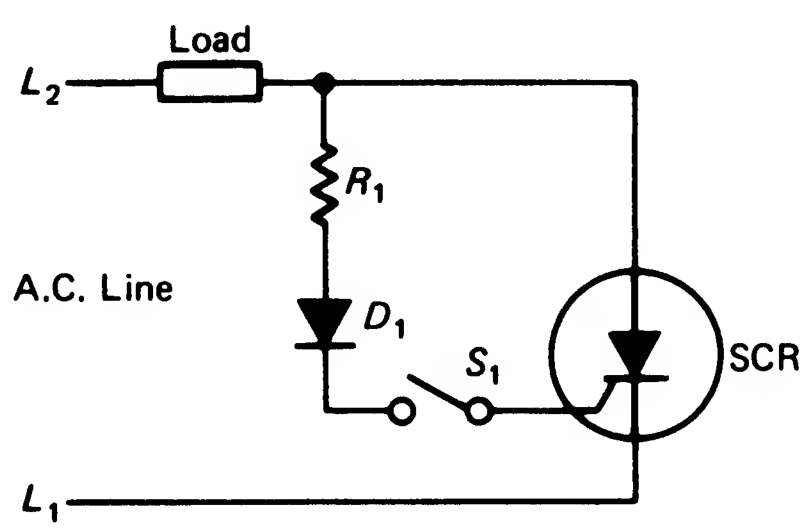


(a) CONTROLLED FULL WAVE

(b) CONTROLLED FULL WAVE (c) CONTROLLED FULL WAVE FOR AC OR DC

Fig. 10–50. Full-wave ac phase control. *(General Electric Co., Semiconductor Products Dept.)*

Fig. 10–51. Resistance triggering.



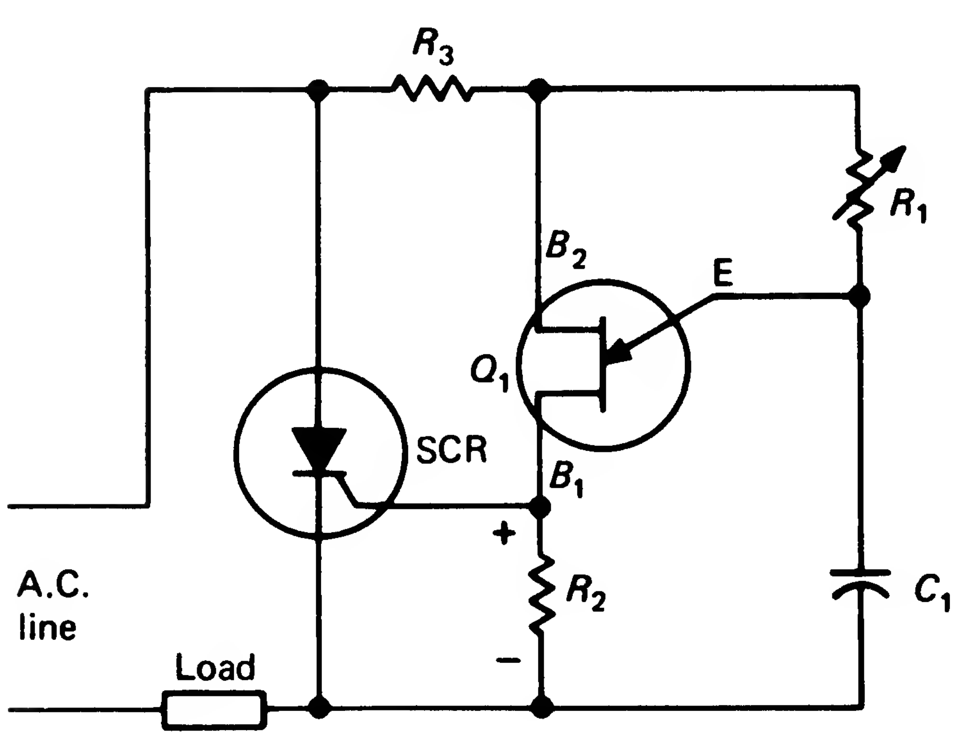


Fig. 10–52. Half-wave with phase control with UJT triggering.

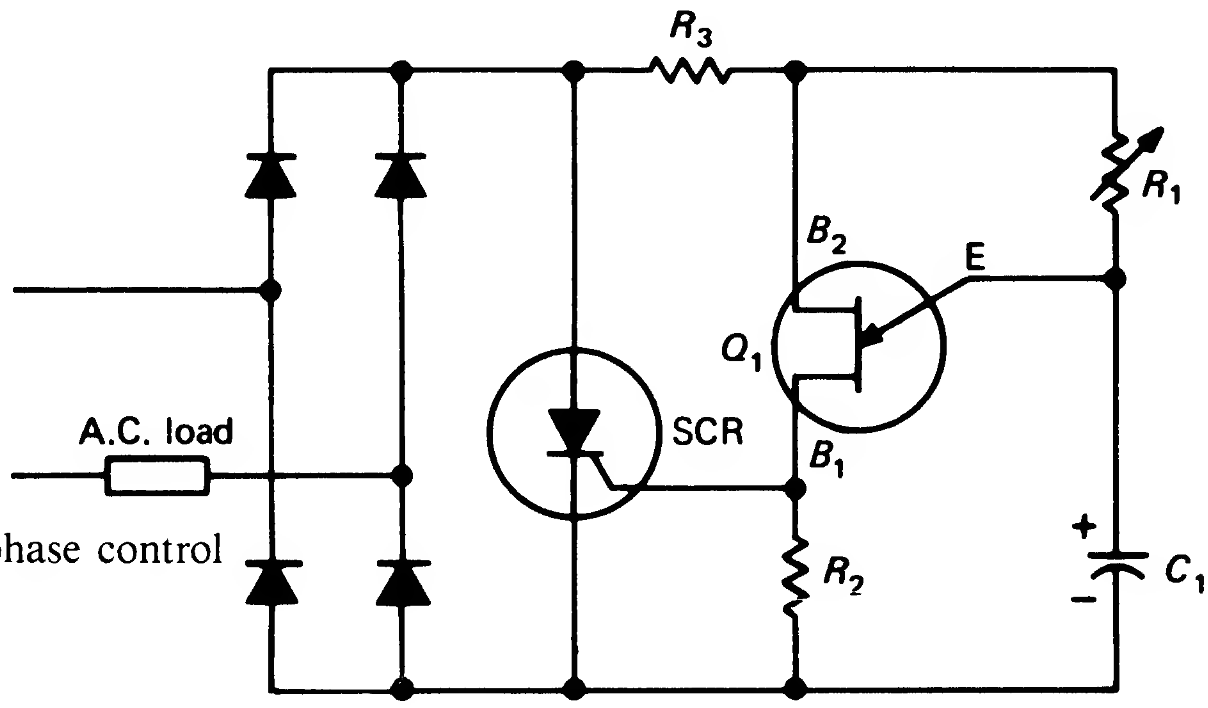


Fig. 10-53. Full-wave phase control with UJT triggering.

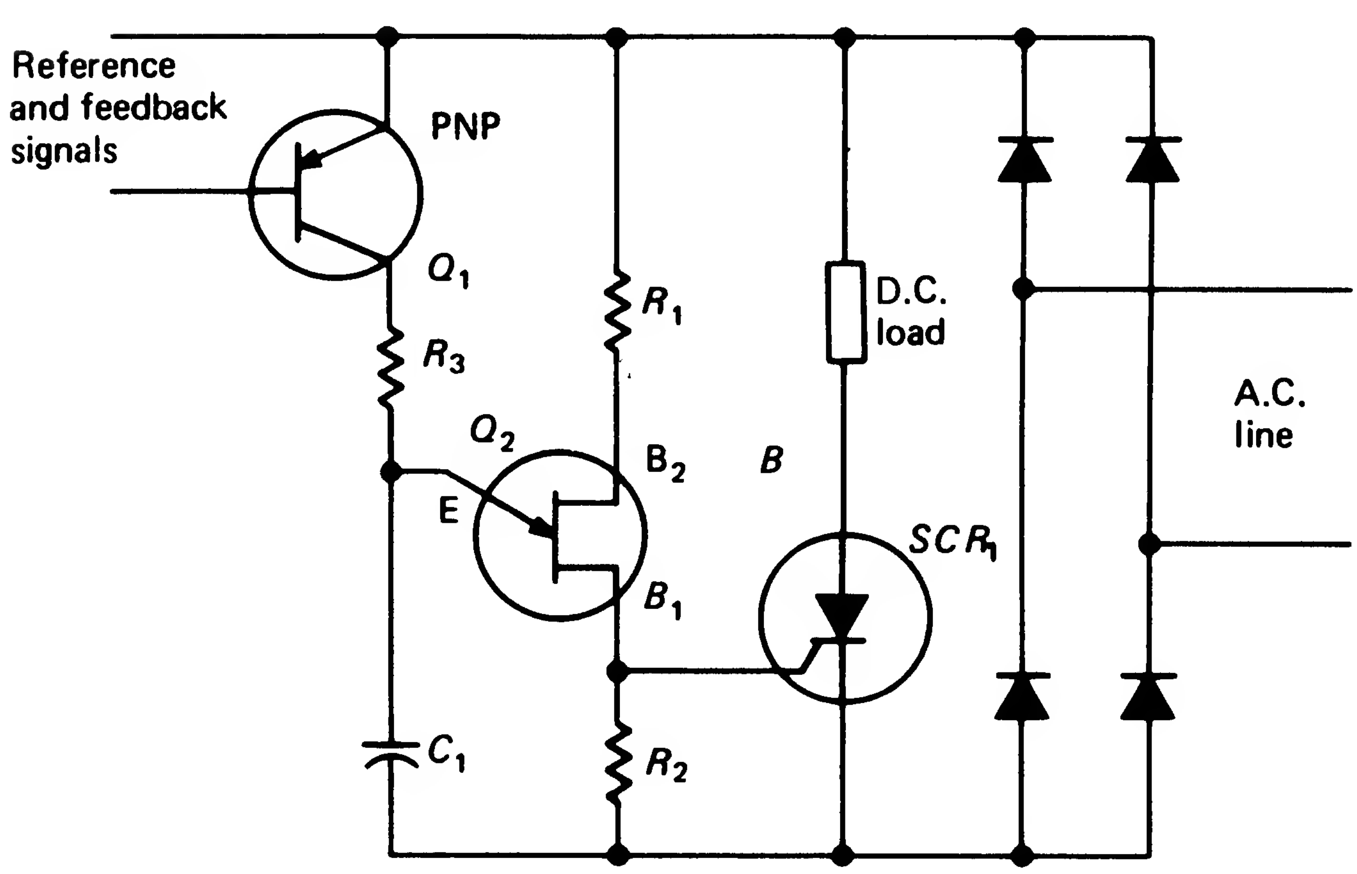


Fig. 10-54. PNP transistor and UJT connected in firing circuit.

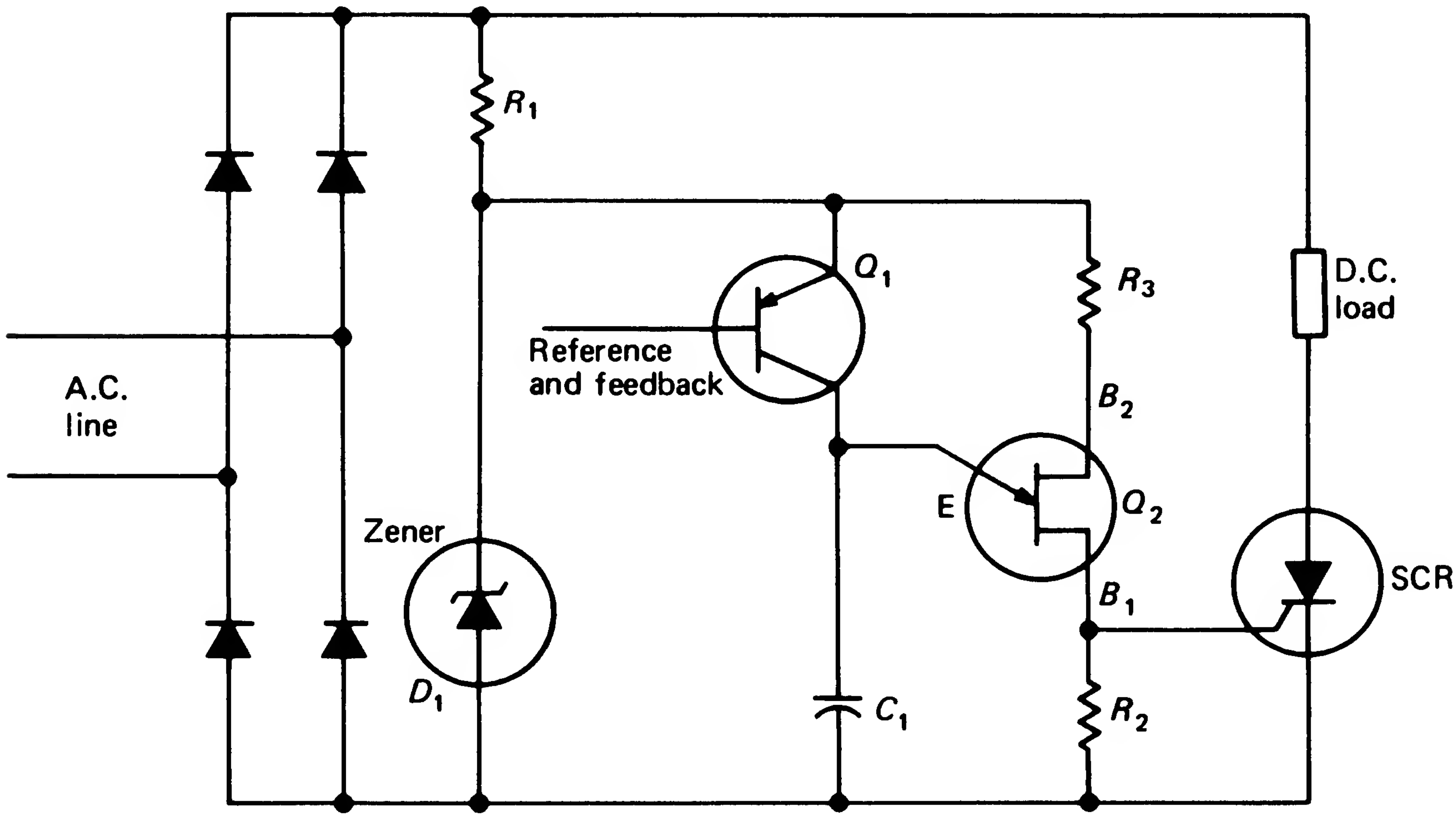


Fig. 10–55. UJT and transistor control stabilized by a Zener voltage.

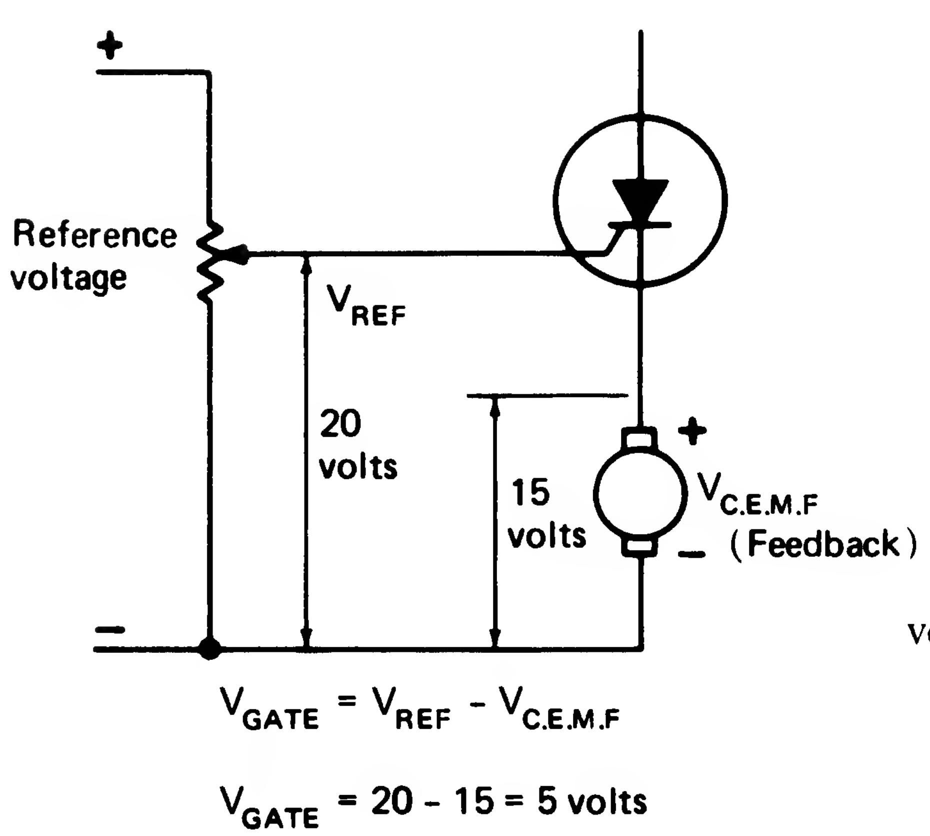


Fig. 10–56. Reference and feedback voltages.

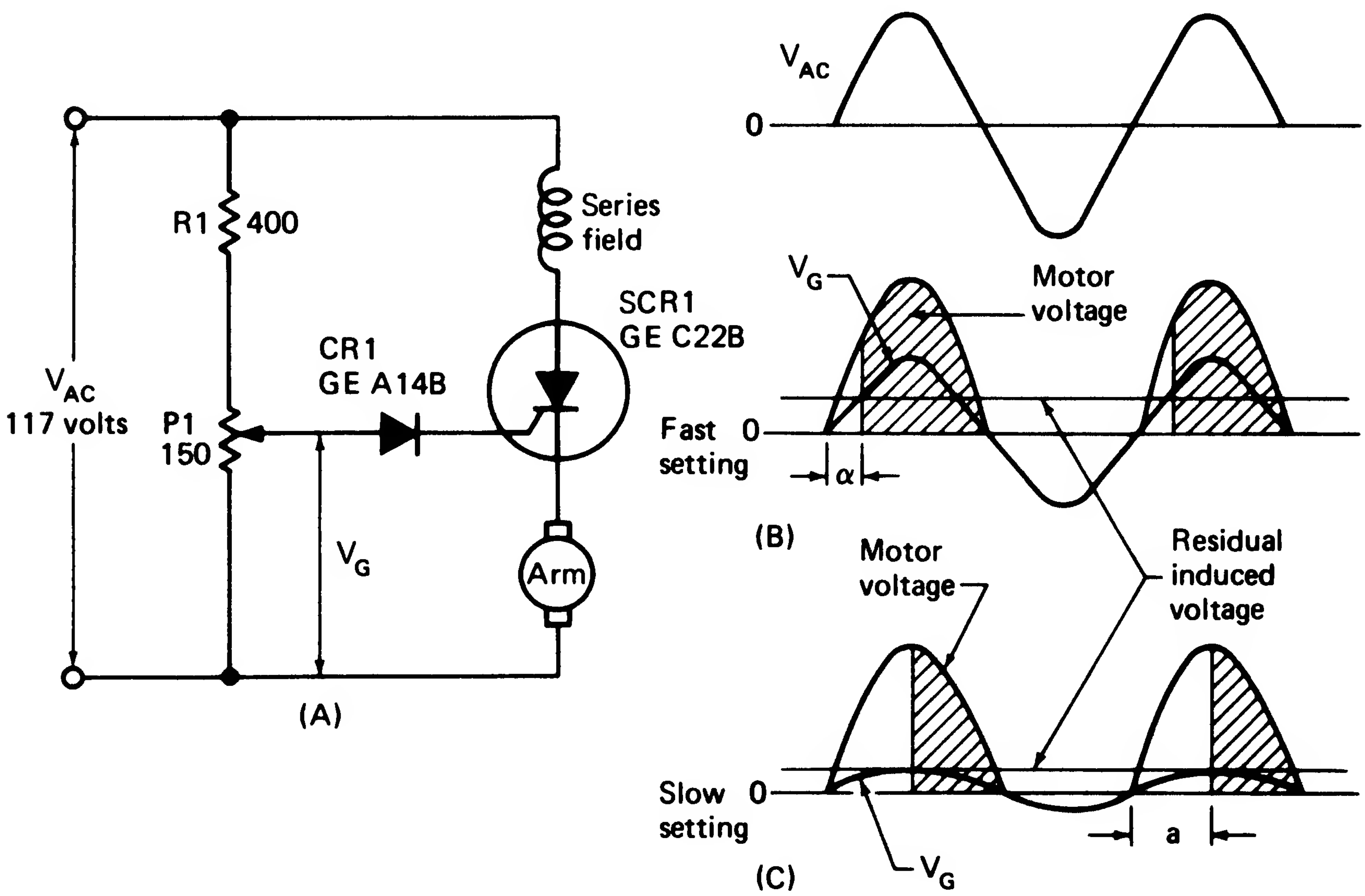


Fig. 10-57. Half-wave control with feedback. *(General Electric Co., Semiconductor Products Dept.)*

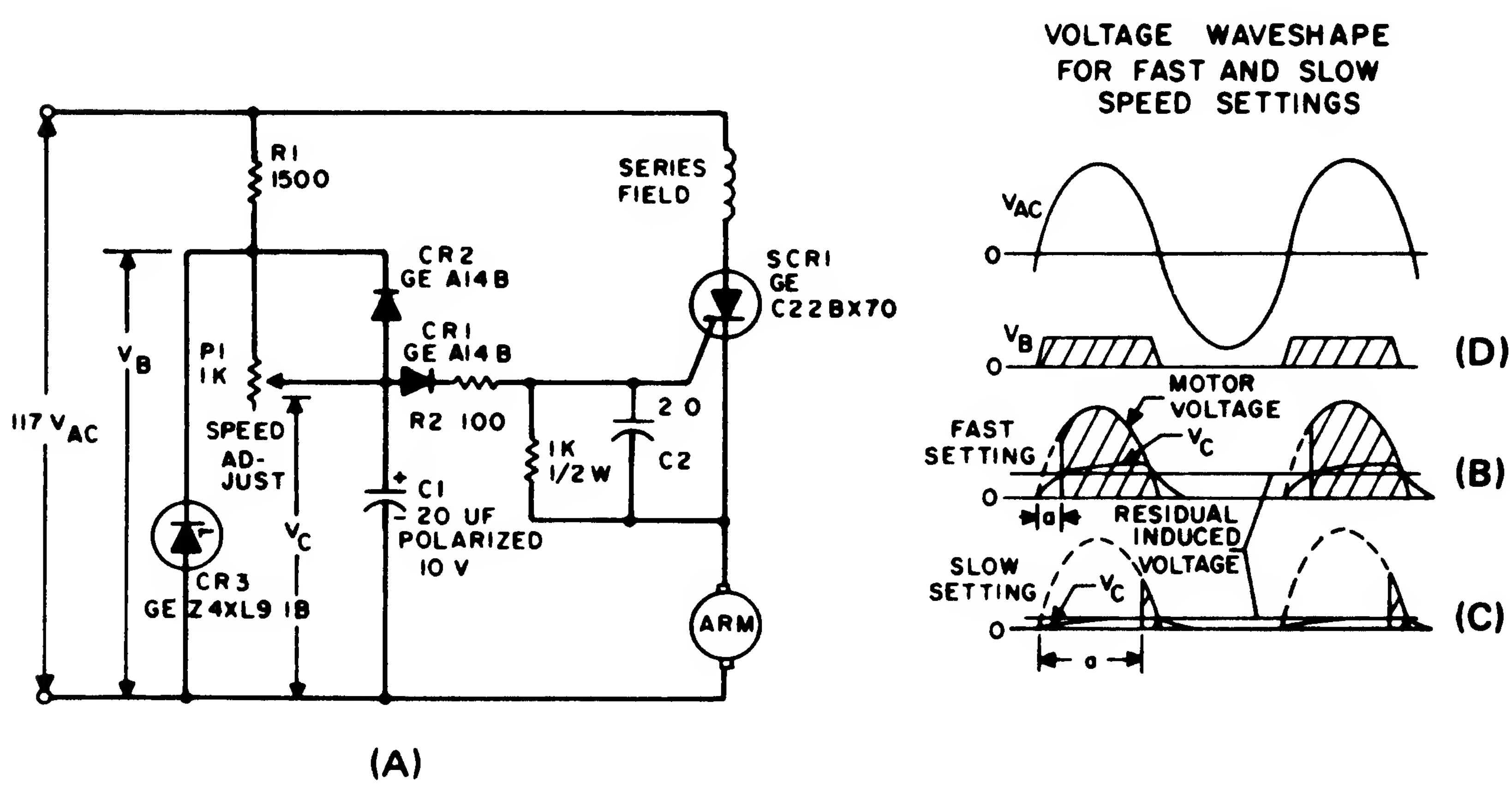


Fig. 10-58. Improved half-wave control with feedback. *(General Electric Co., Semiconductor Products Dept.)*

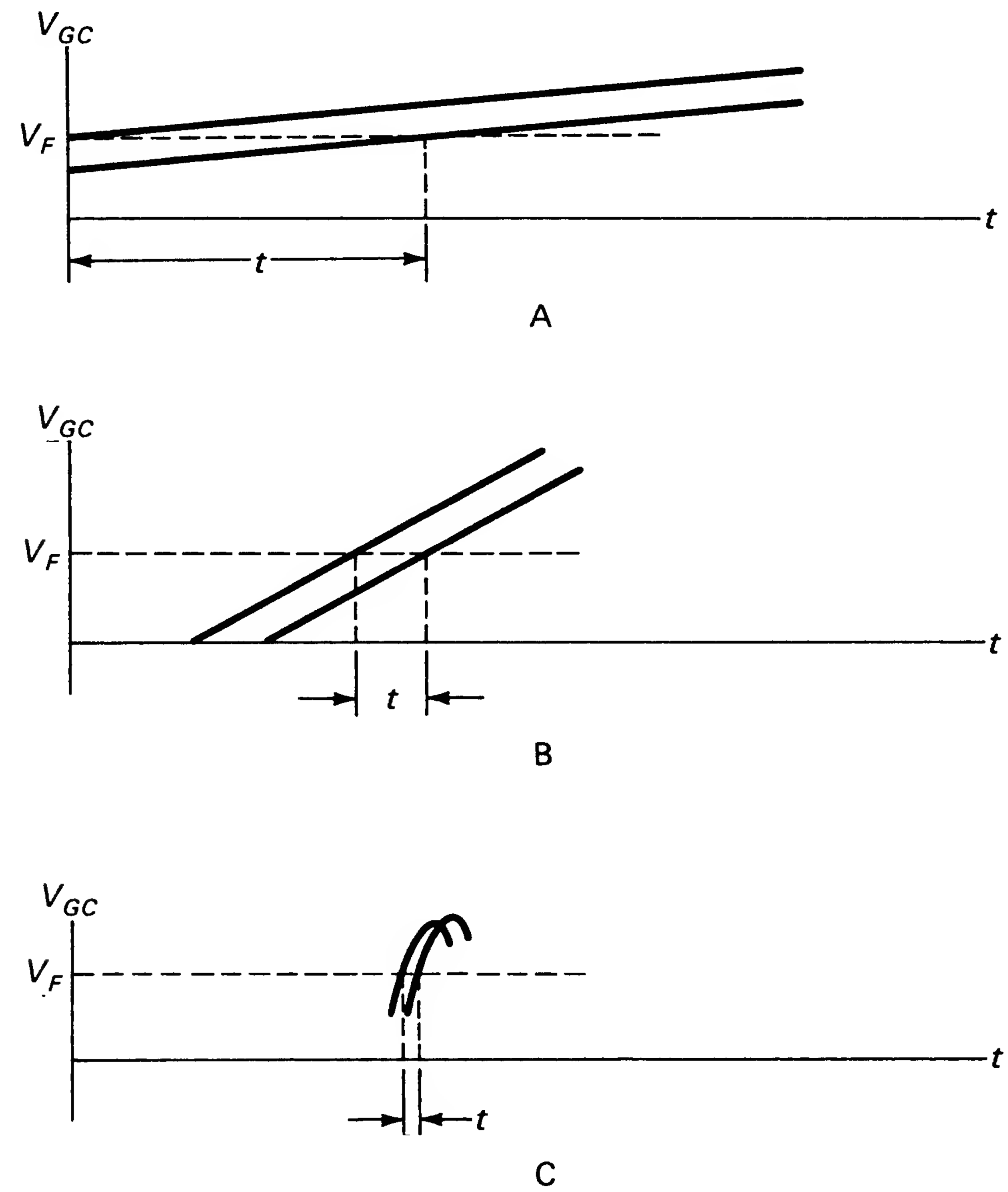


Fig. 10-59. Firing time shifts versus slope of V_{GC}.

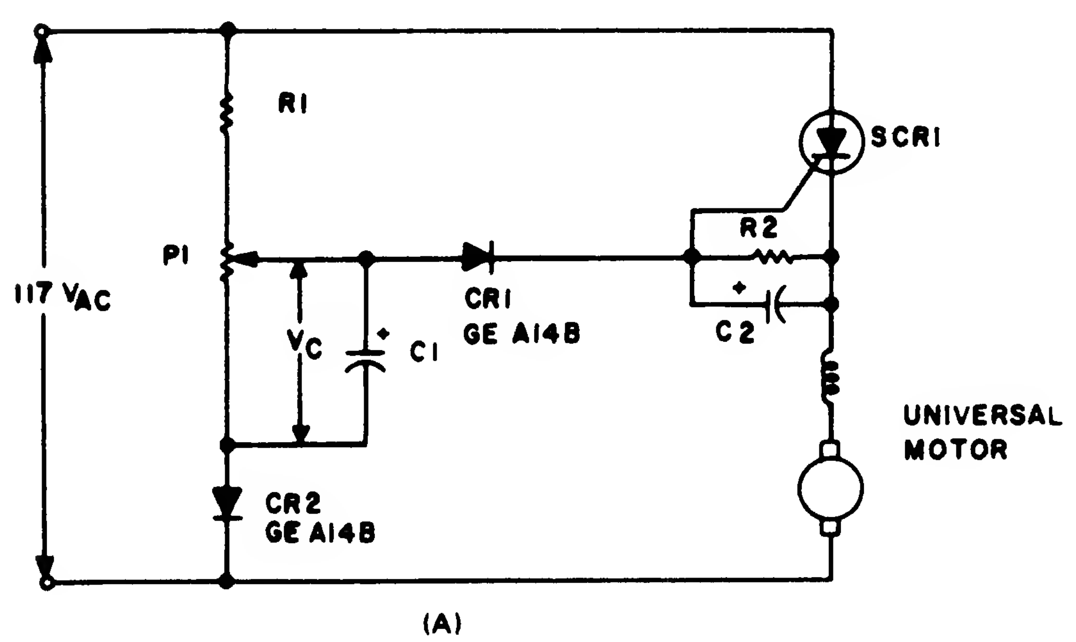
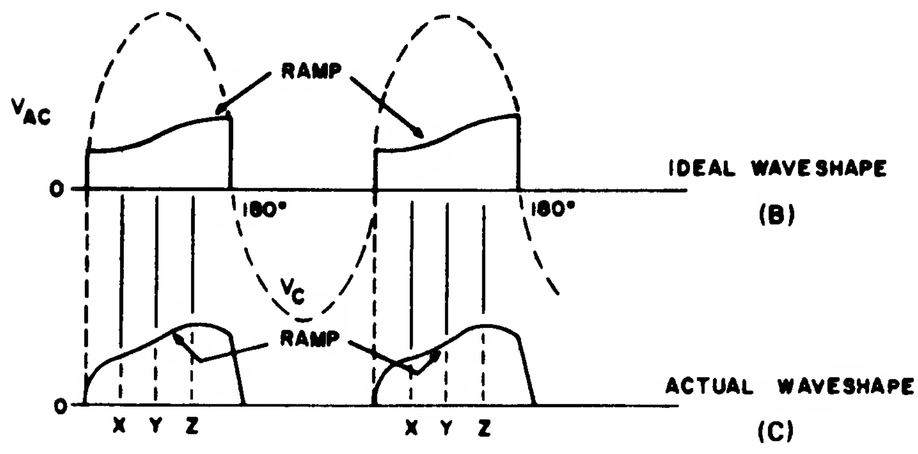


Fig. 10-60 (*con't.*) Universal motor control with feedback. *(General Electric Co., Semiconductor Products Dept.)*



COMPONENT VALUES FOR THE CIRCUIT

	LOW UP TO 1AMP NAMEPLATE	MEDIUM UP TO 3AMP NAMEPLATE	HIGH UP TO 5AMP NAMEPLATE
P1	10K 1W	1K 2W	1K 2W
R1	47K 1/2W	3.3K 2W	3.3K 2W
R2	1K 1/2W	150 1/2W OPTIONAL	150 1/2W OPTIONAL
C1	.5μf 10V	10μf 10V	10μf 10V
C2	1μf 10V	1μf 10V OPTIONAL	.1μf 10V OPTIONAL
SCR1	GE C106B	GE C228X70	GE C 35B

(D)

Fig. 10-60 (*continued*) Universal motor control with feedback. *(General Electric Co., Semiconductor Products Dept.)*

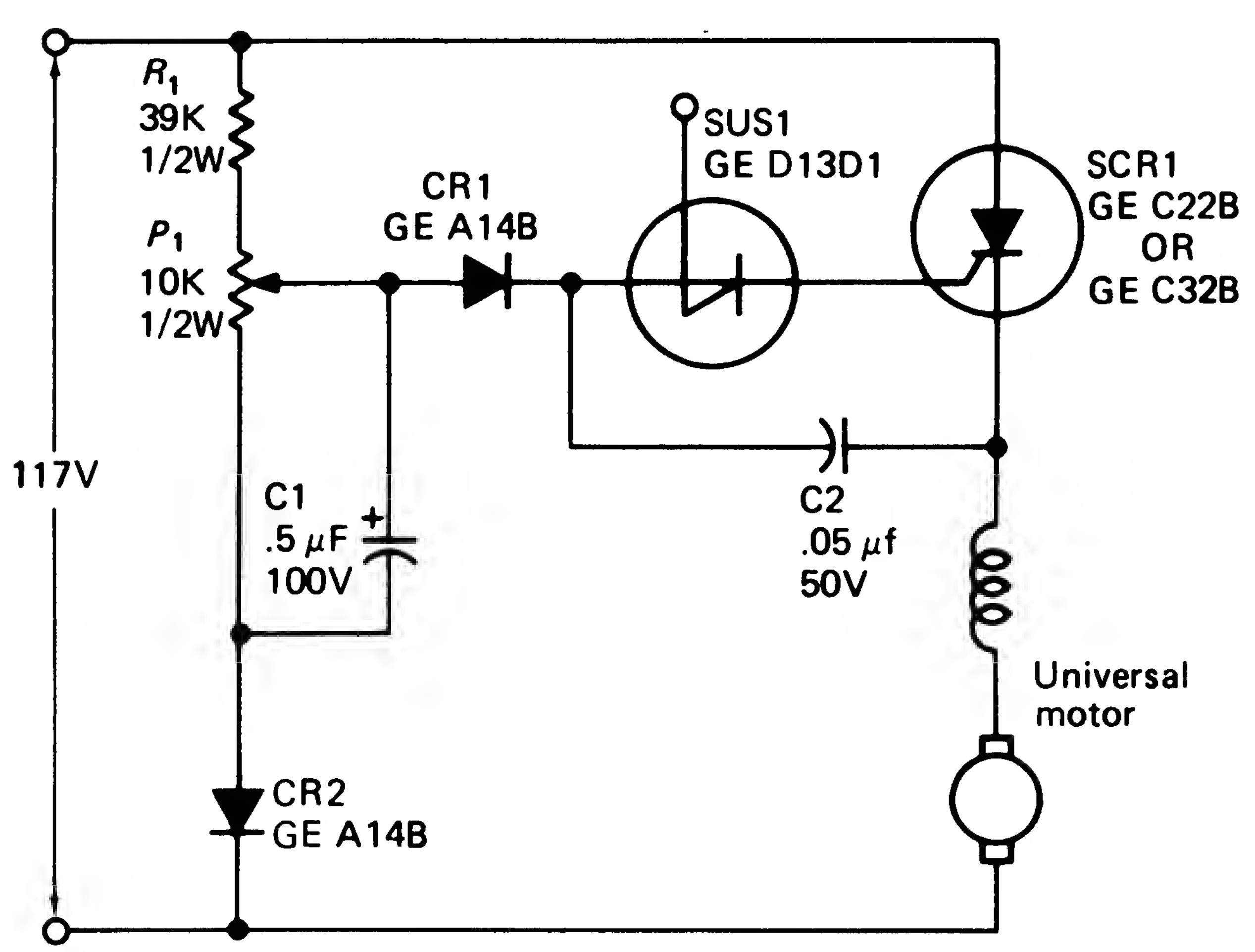


Fig. 10-61. SUS triggered universal motor speed control with feedback. *(General Electric Co., Semiconductor Products Dept.)*

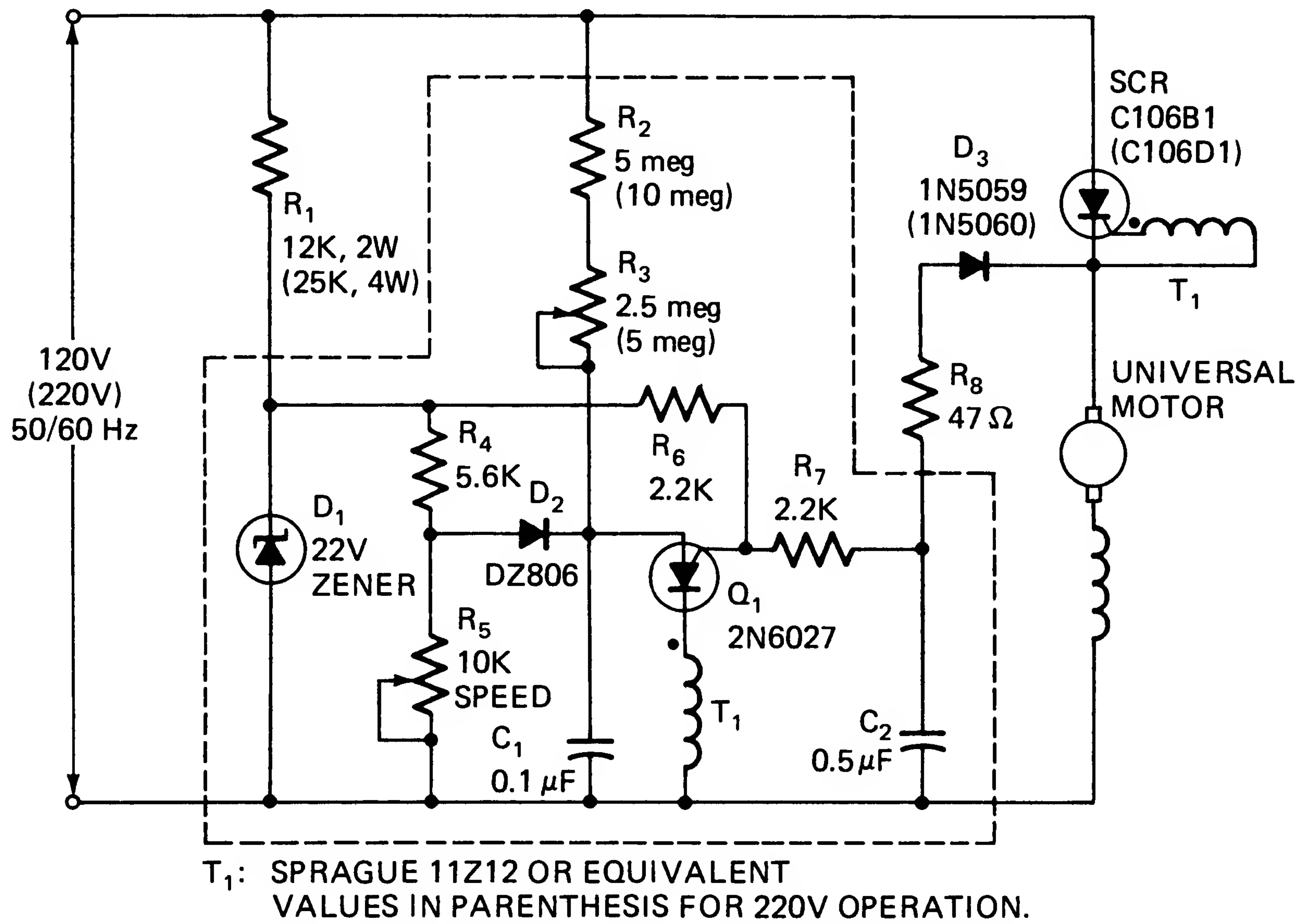


Fig. 10-62. PUT triggered universal motor control with feedback. *(General Electric Co., Semiconductor Products Dept.)*

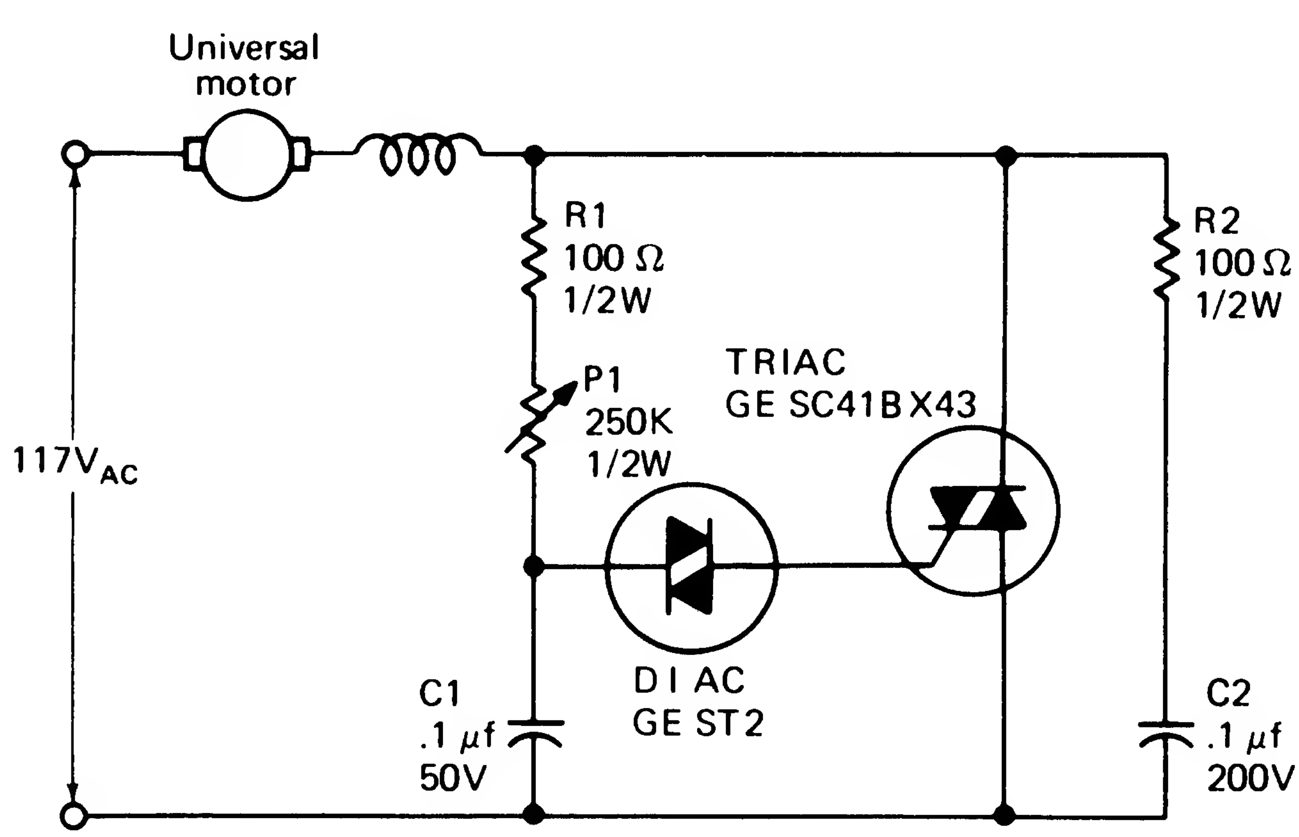


Fig. 10-63. Full-wave ac control without feedback. *(General Electric Co., Semiconductor Products Dept.)*

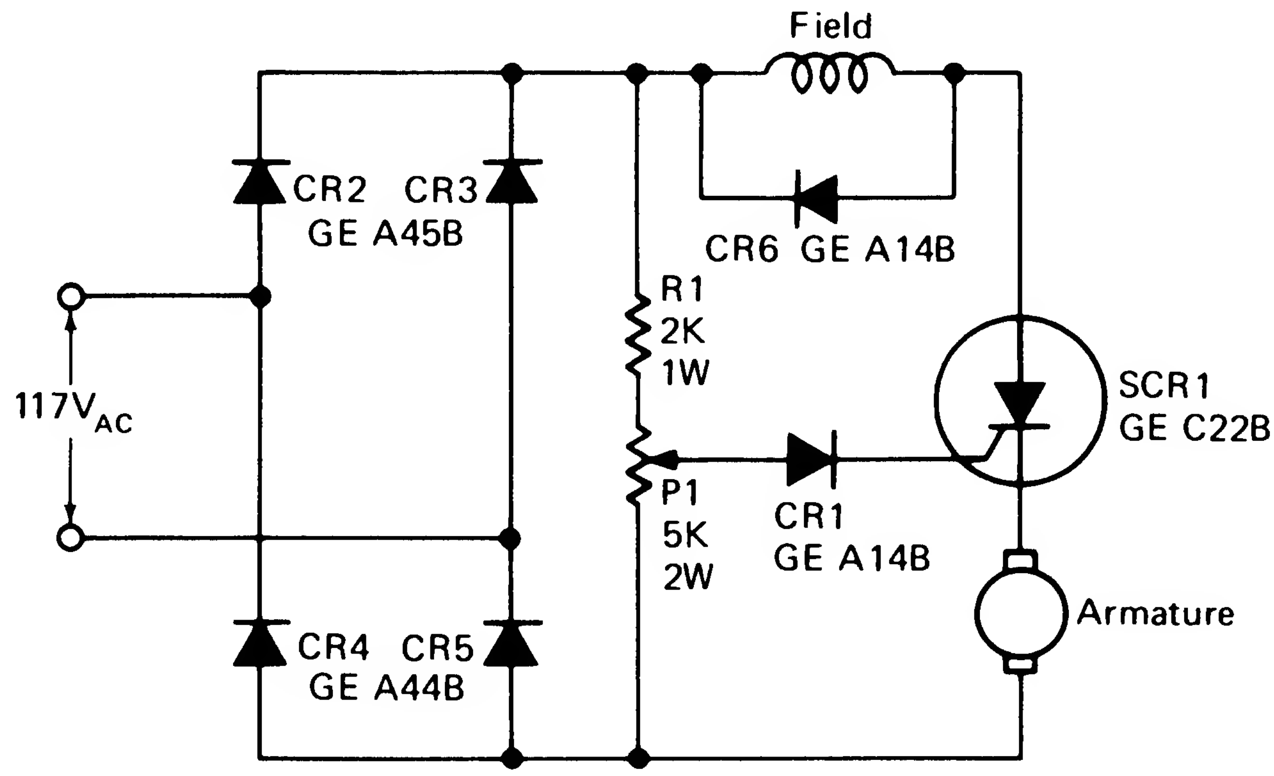


Fig. 10-64. Full-wave dc control with feedback. *(General Electric Co., Semiconductor Products Dept.)*

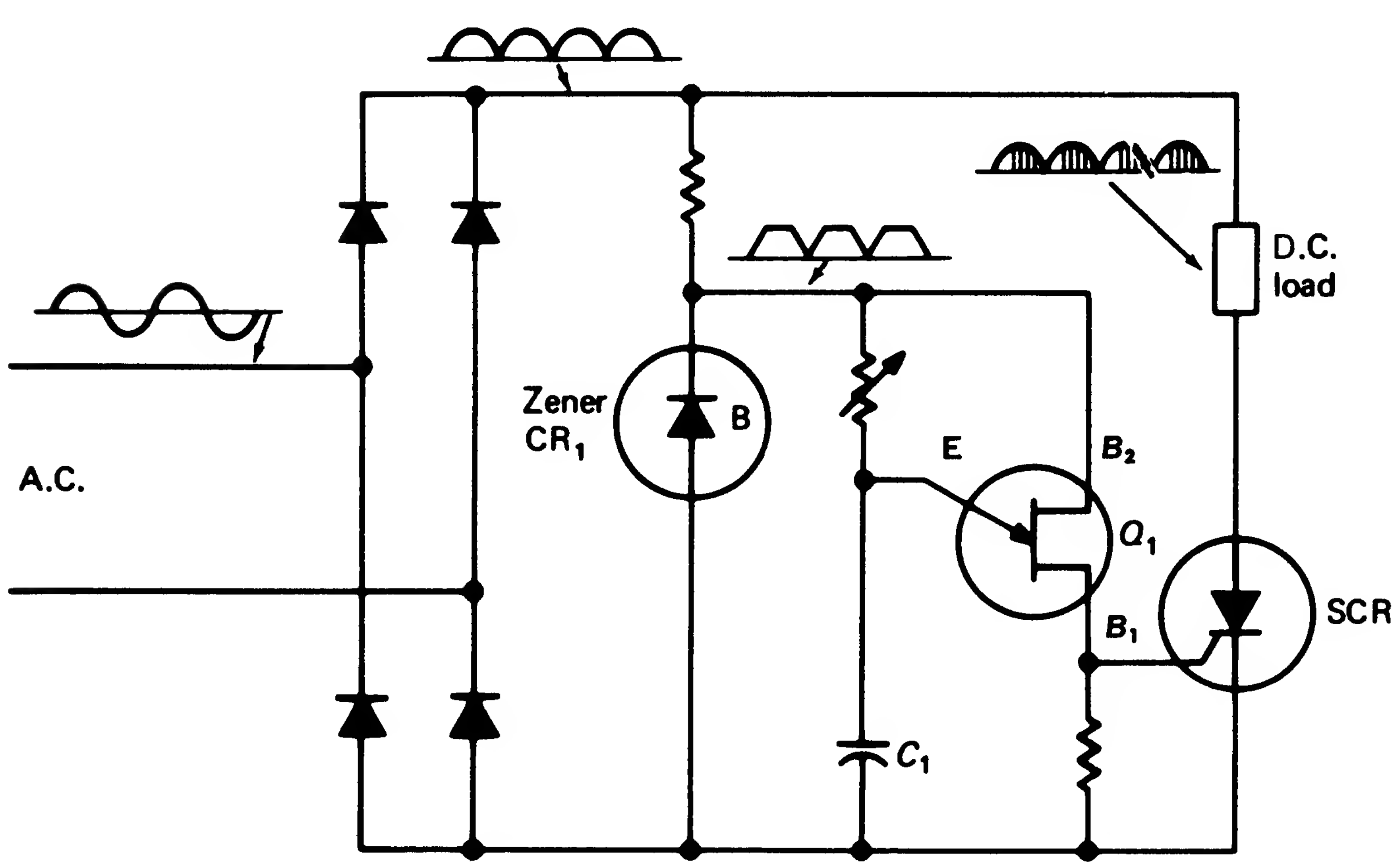


Fig. 10-65. Full-wave control with precision firing. *(General Electric Co., Semiconductor Products Dept.)*

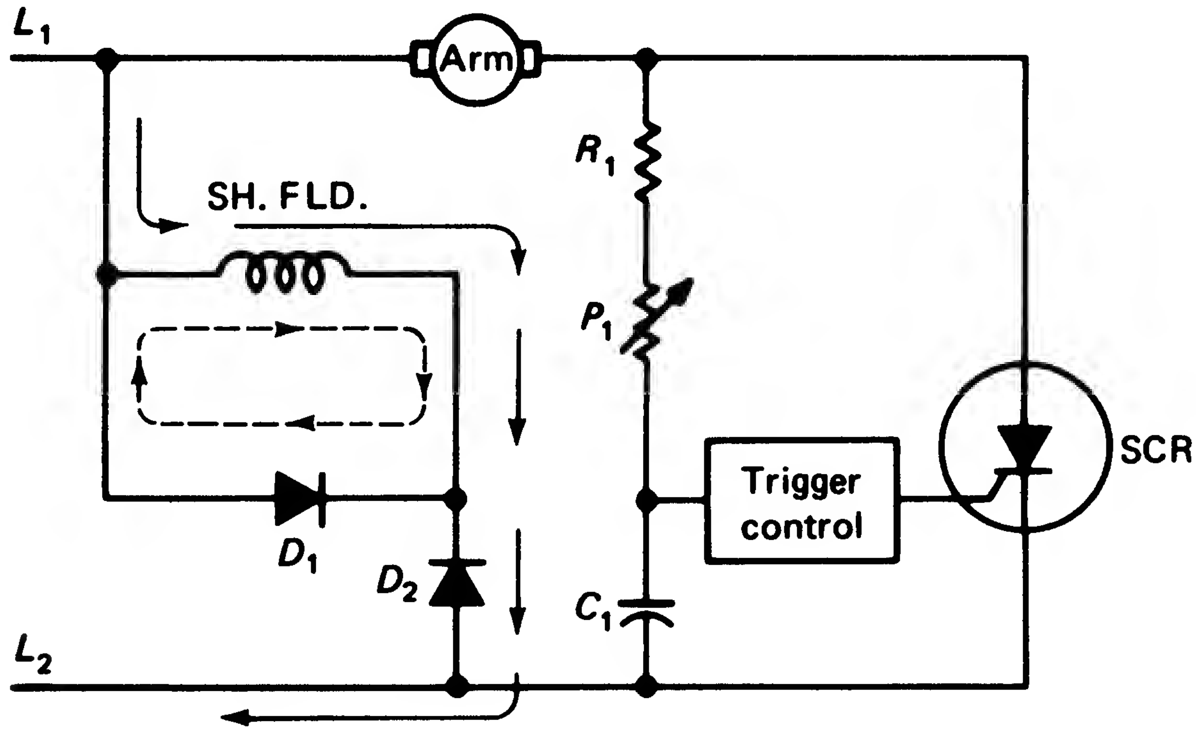


Fig. 10–66. Half-wave control for a shunt motor without feedback.

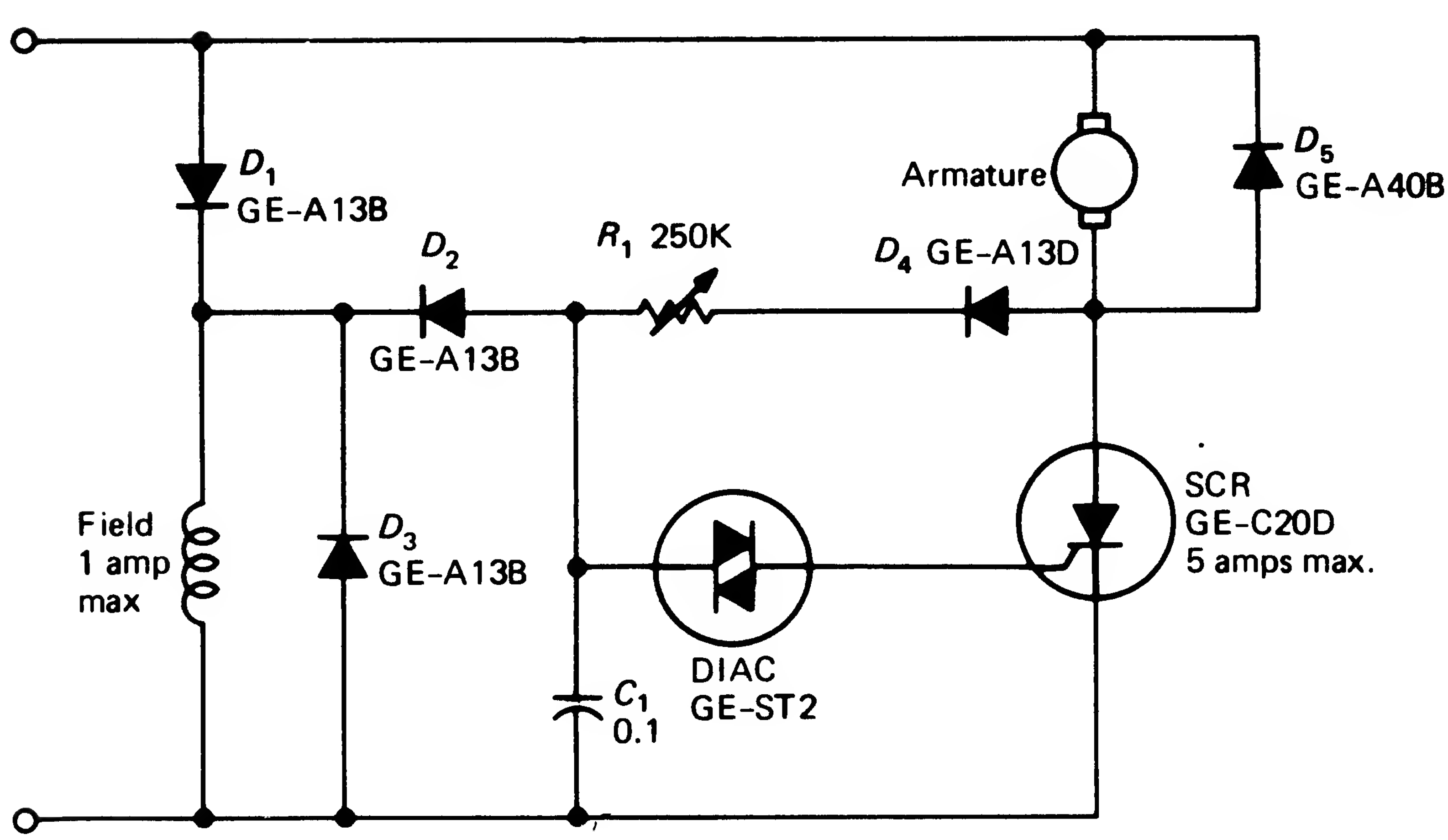


Fig. 10–67. Half-wave control for shunt motor with precision firing. *(General Electric Co., Semiconductor Products Dept.)*

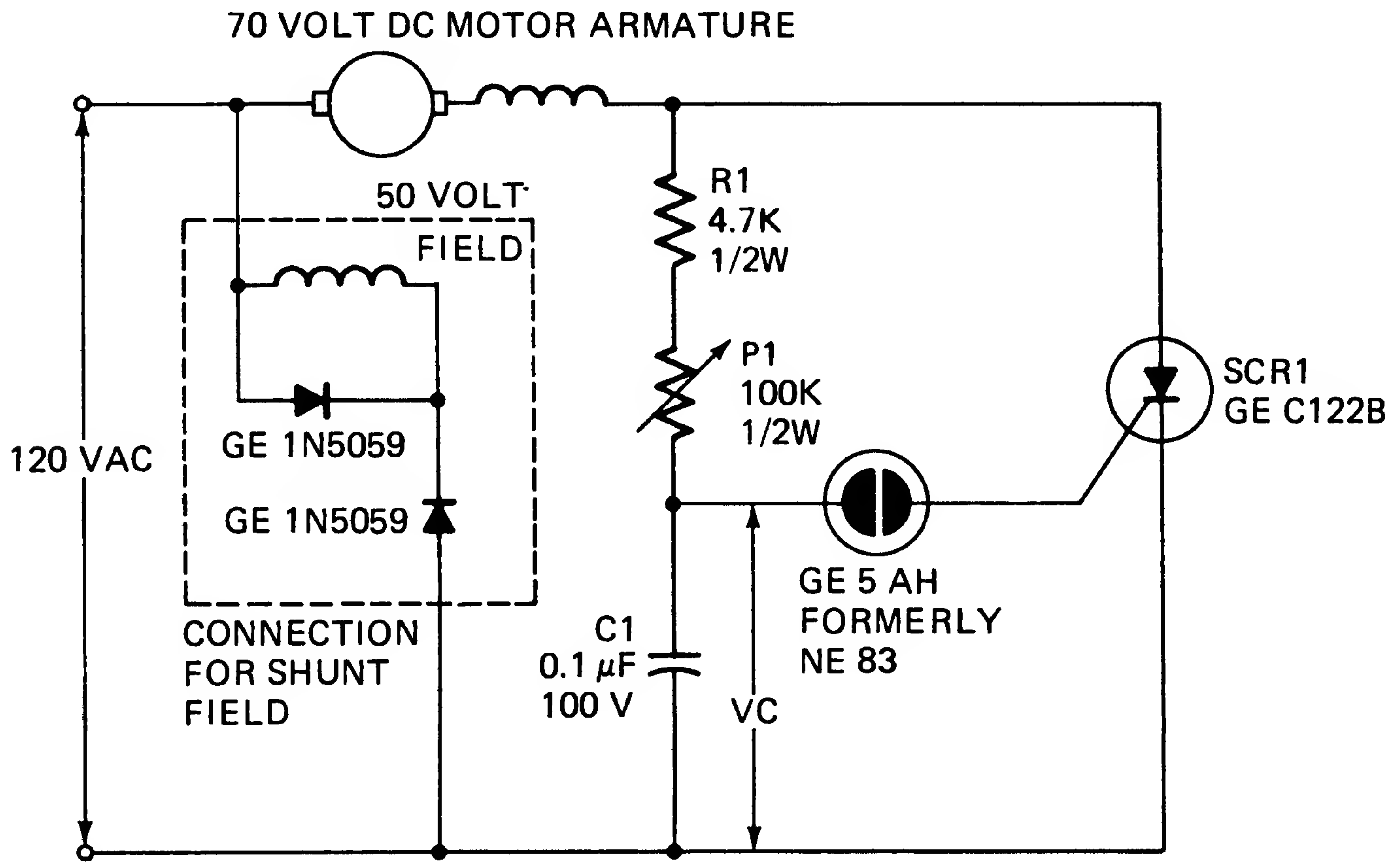


Fig. 10-68. Half-wave control without feedback (neon triggered). *(General Electric Co., Semiconductor Products Dept.)*

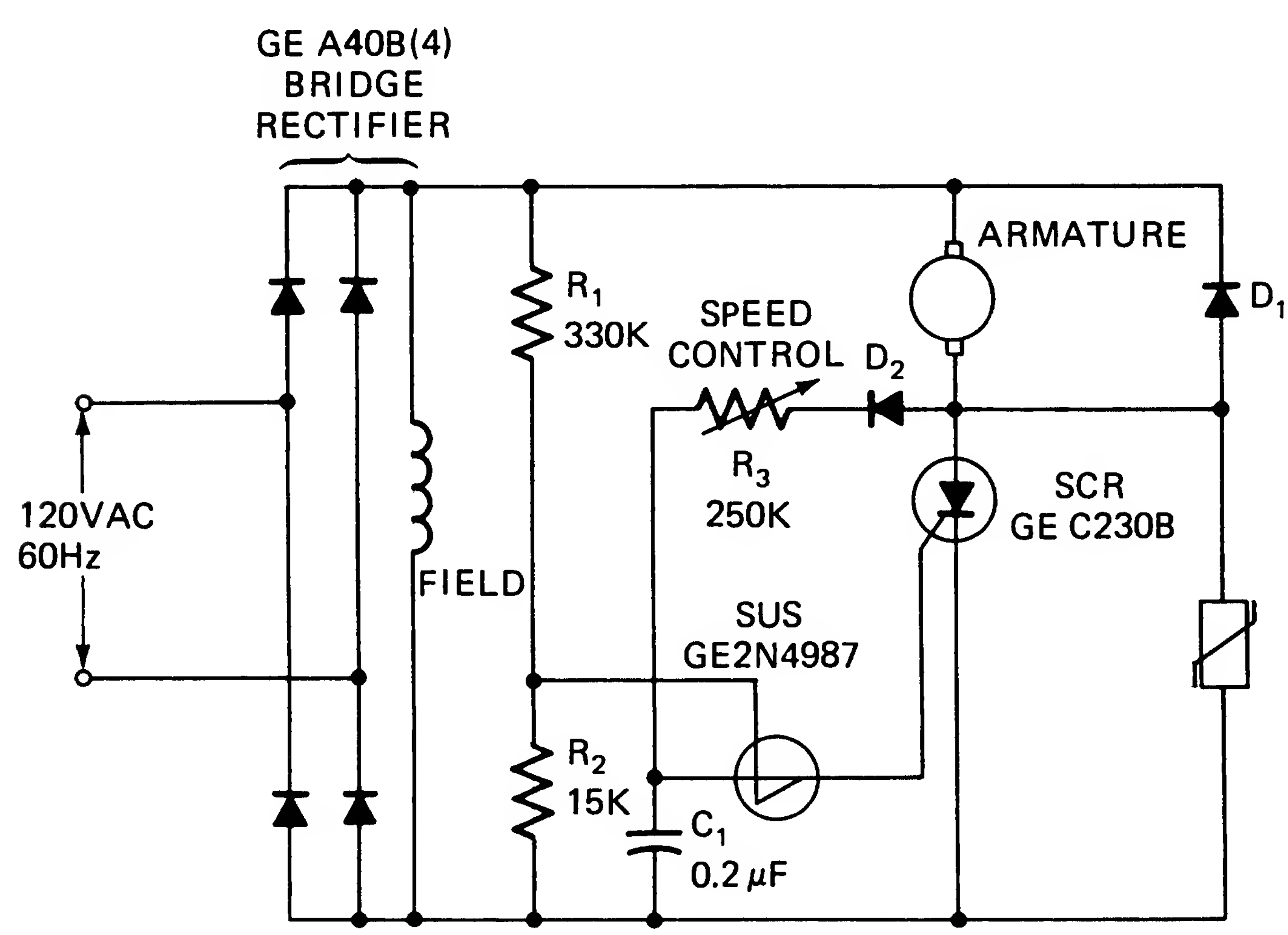


Fig. 10-69. Speed control for ½ hp, 115V shunt motor. *(General Electric Co., Semiconductor Products Dept.)*

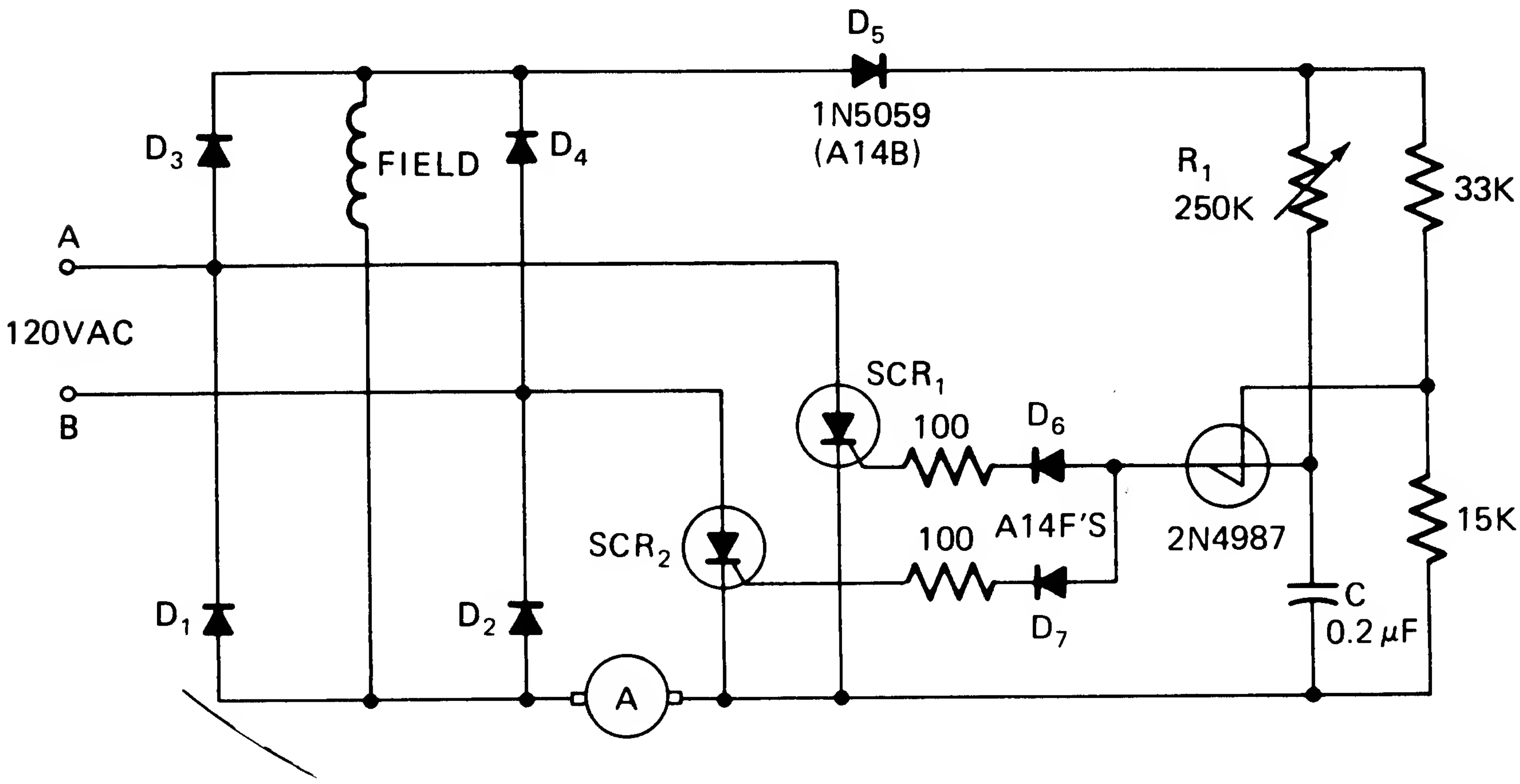
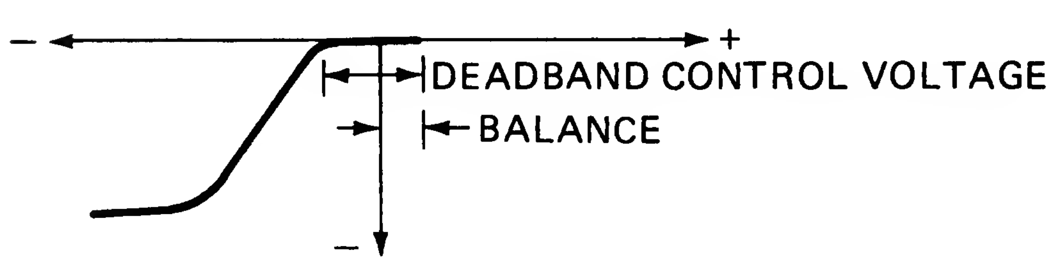


Fig. 10–70. Full-wave SCR shunt or PM motor speed control. *(General Electric Co., Semiconductor Products Dept.)*



Motor Current	Diodes CR_3–CR_6	Triac
1.5 A	A14B	SC141B
4.5 A	A15B	SC141B
4.5 A	A40B/A41B	SC251B

Fig. 10–71. Induction motor speed-torque curves for use with a fan-type load. *(General Electric Co., Semiconductor Products Dept.)*

Figure **10**–70; **10**–71

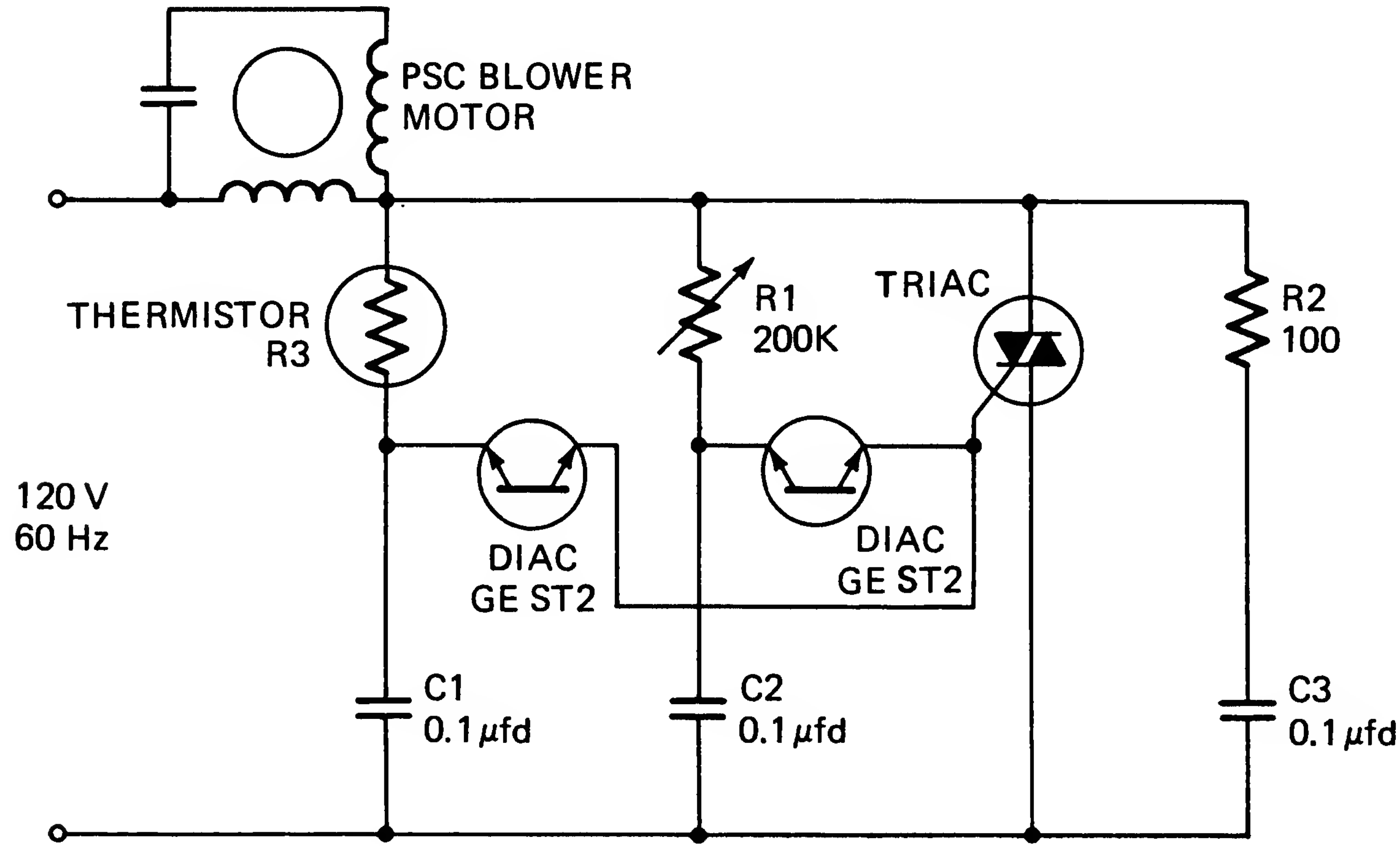


Fig. 10–72. Furnace blower control. *(General Electric Co., Semiconductor Products Dept.)*

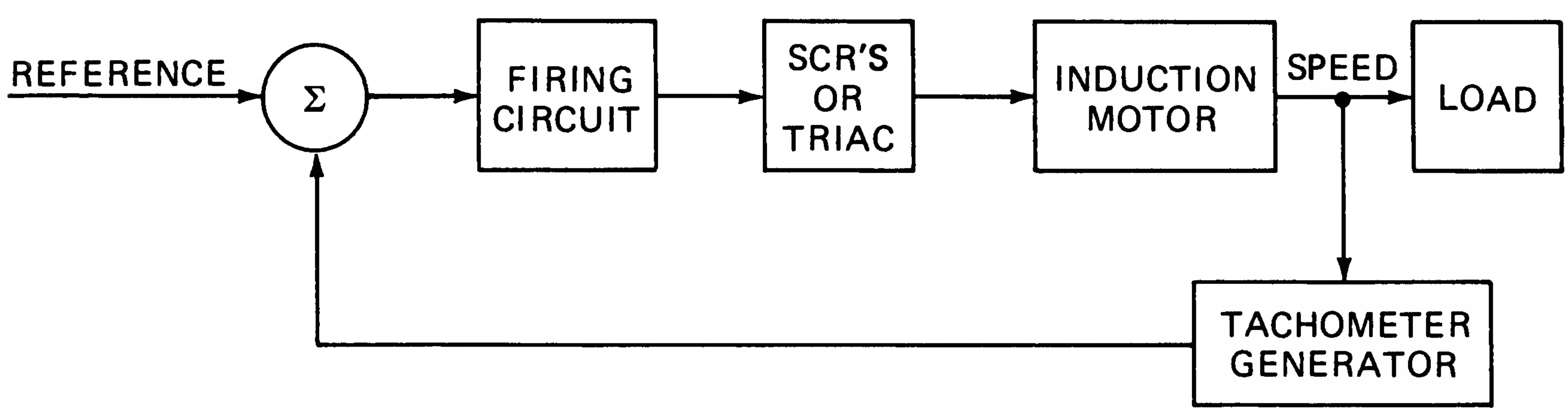


Fig. 10–73. Induction motor speed control with tachometer: block diagram. *(General Electric Co., Semiconductor Products Dept.)*

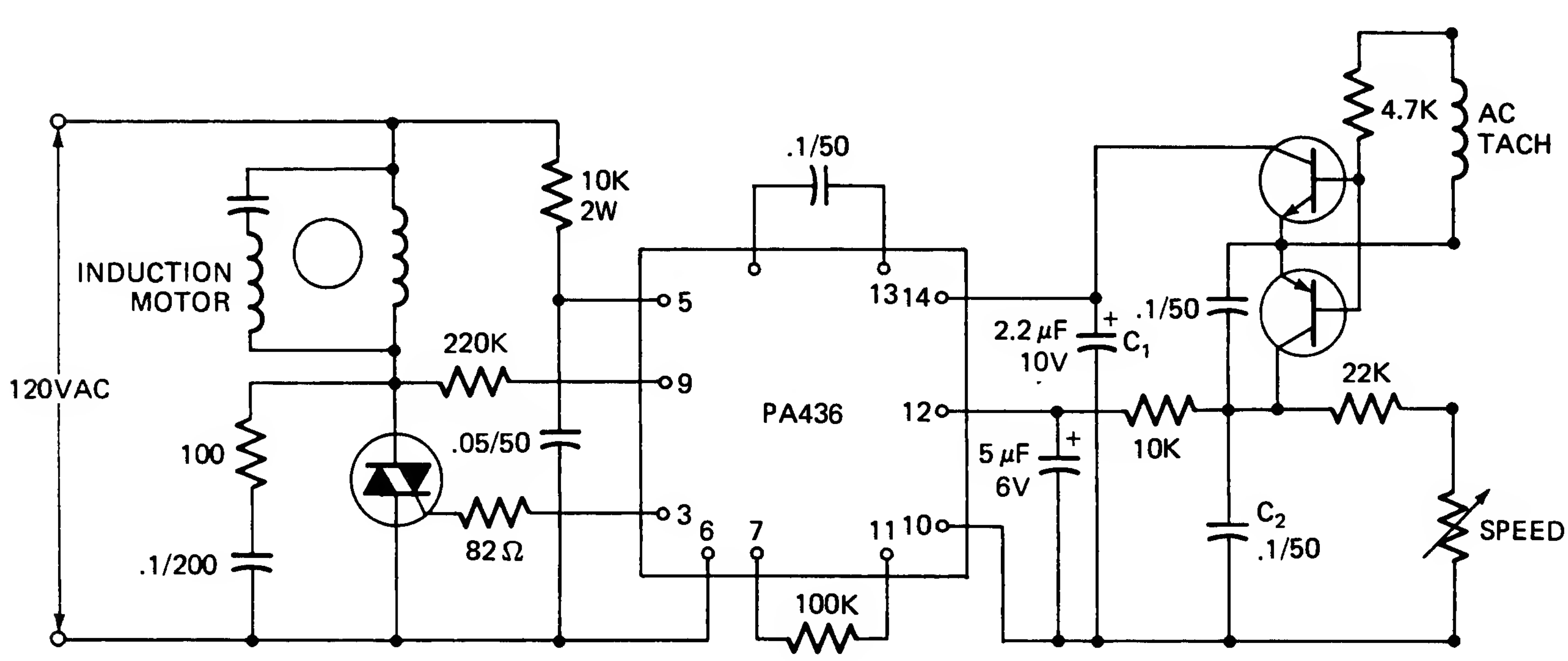


Fig. 10–74. Induction motor speed control. *(General Electric Co., Semiconductor Products Dept.)*

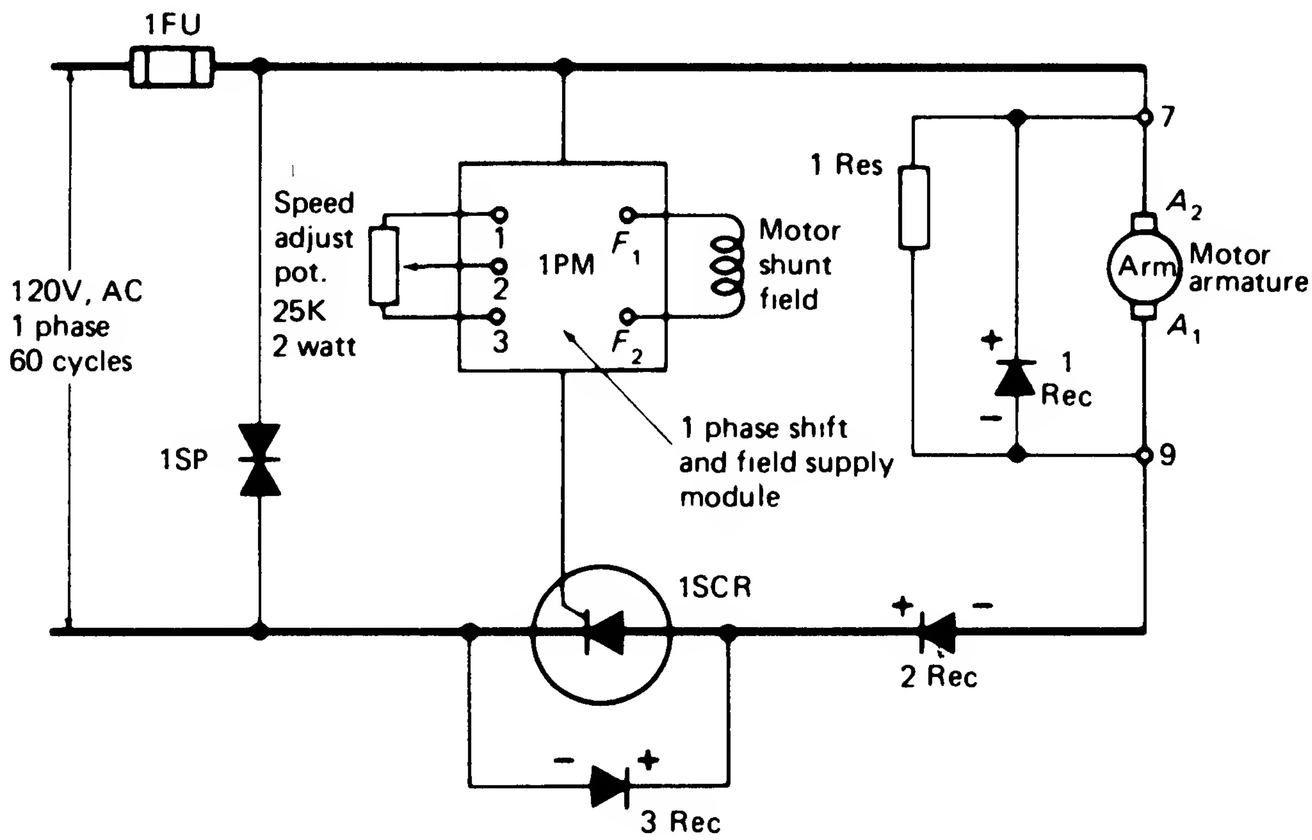


Fig. 10-75. Protecting the SCR by means of diodes, fuses and surge protectors. *(Square D Co.)*

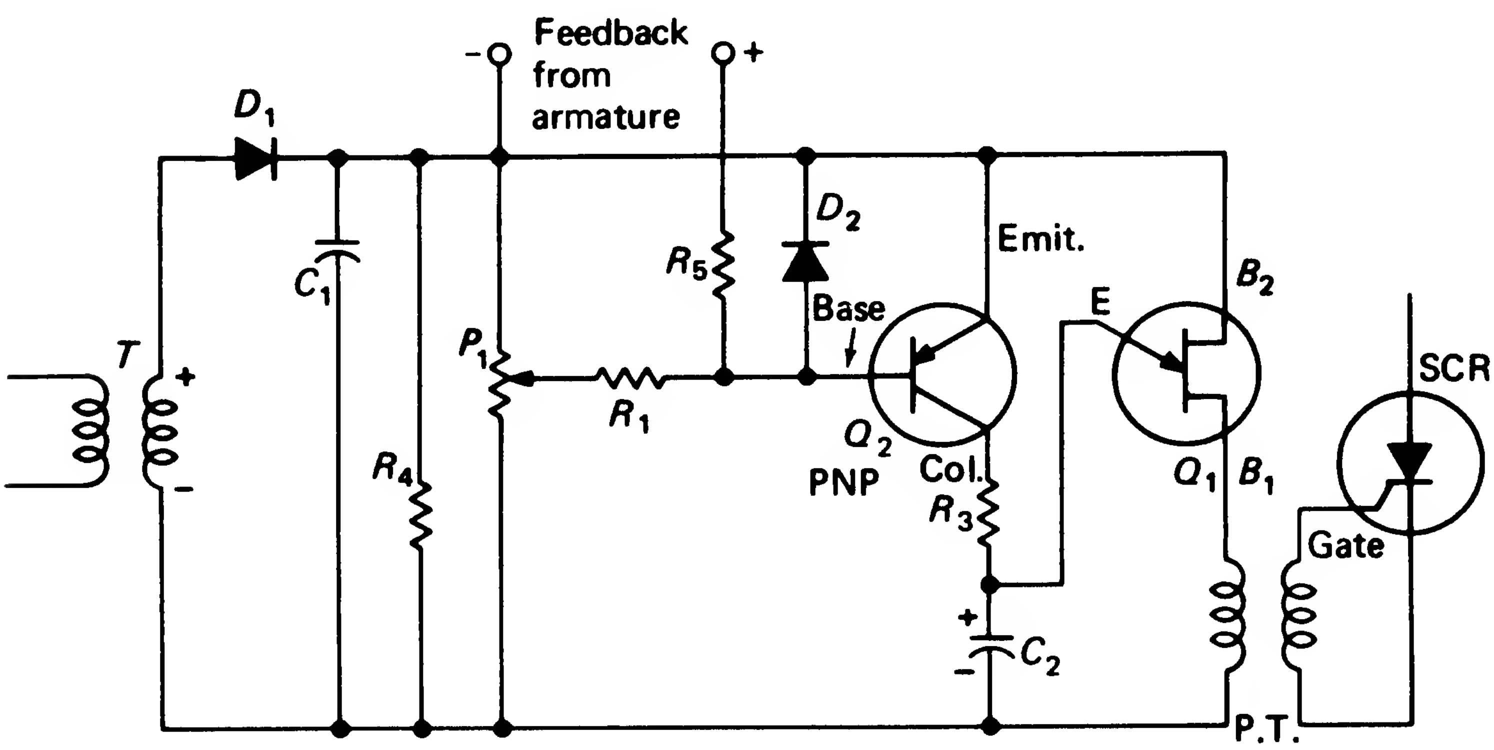


Fig. 10-76. Firing circuit using transistor Q_2 for amplifying the error signal.

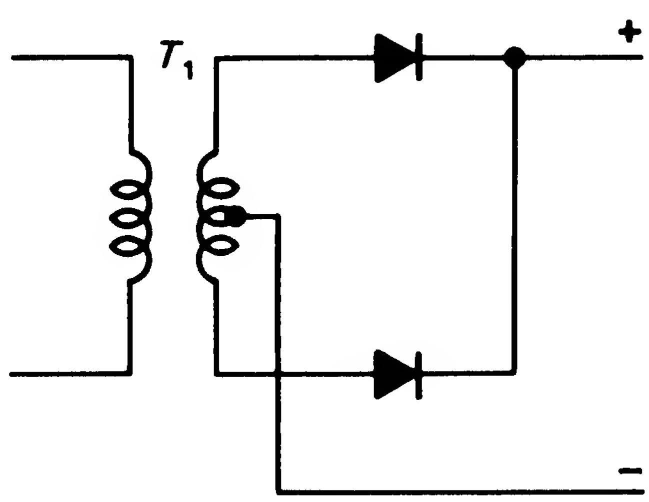


Fig. 10-77. Full-wave reference supply voltage.

Figure **10**–75; **10**–76; **10**–77

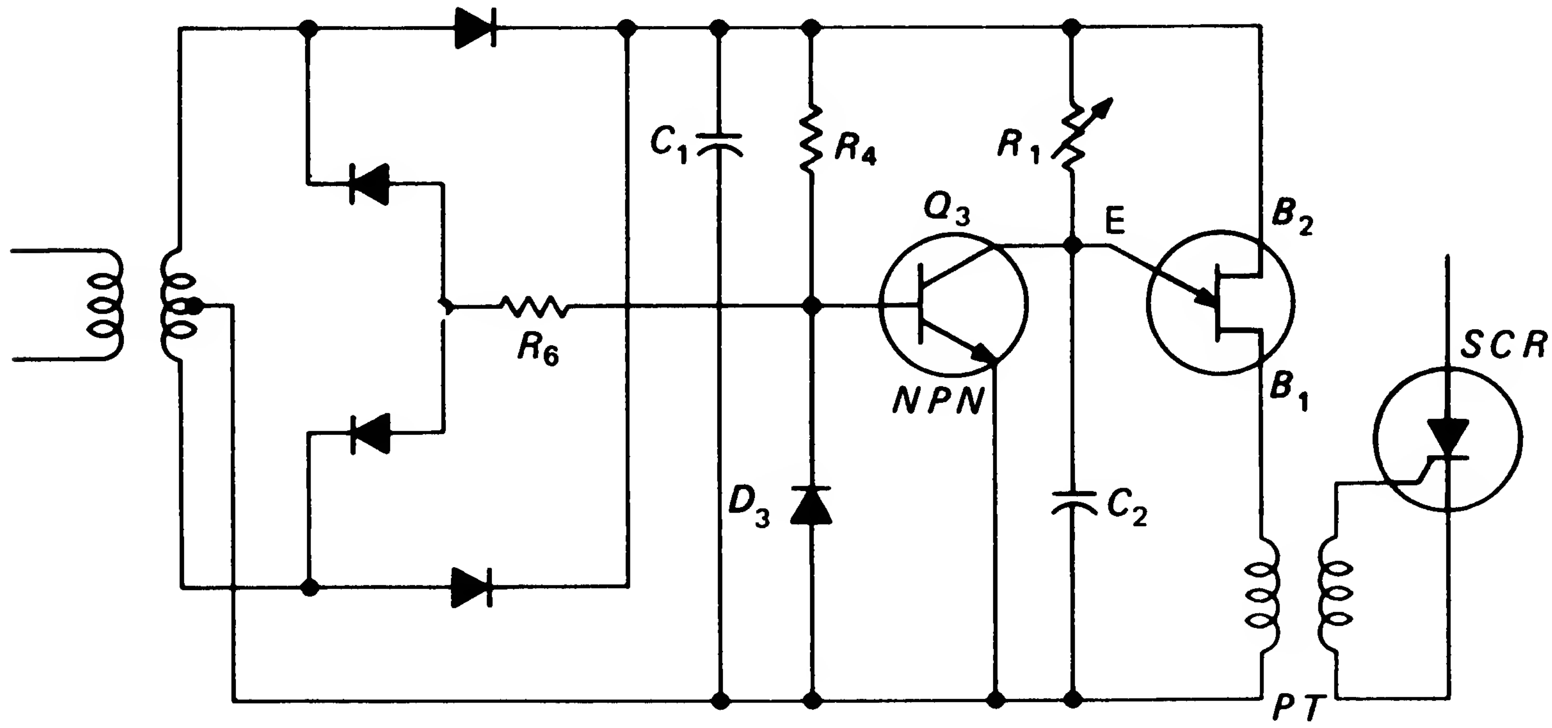


Fig. 10–78. Precision firing using a transistor.

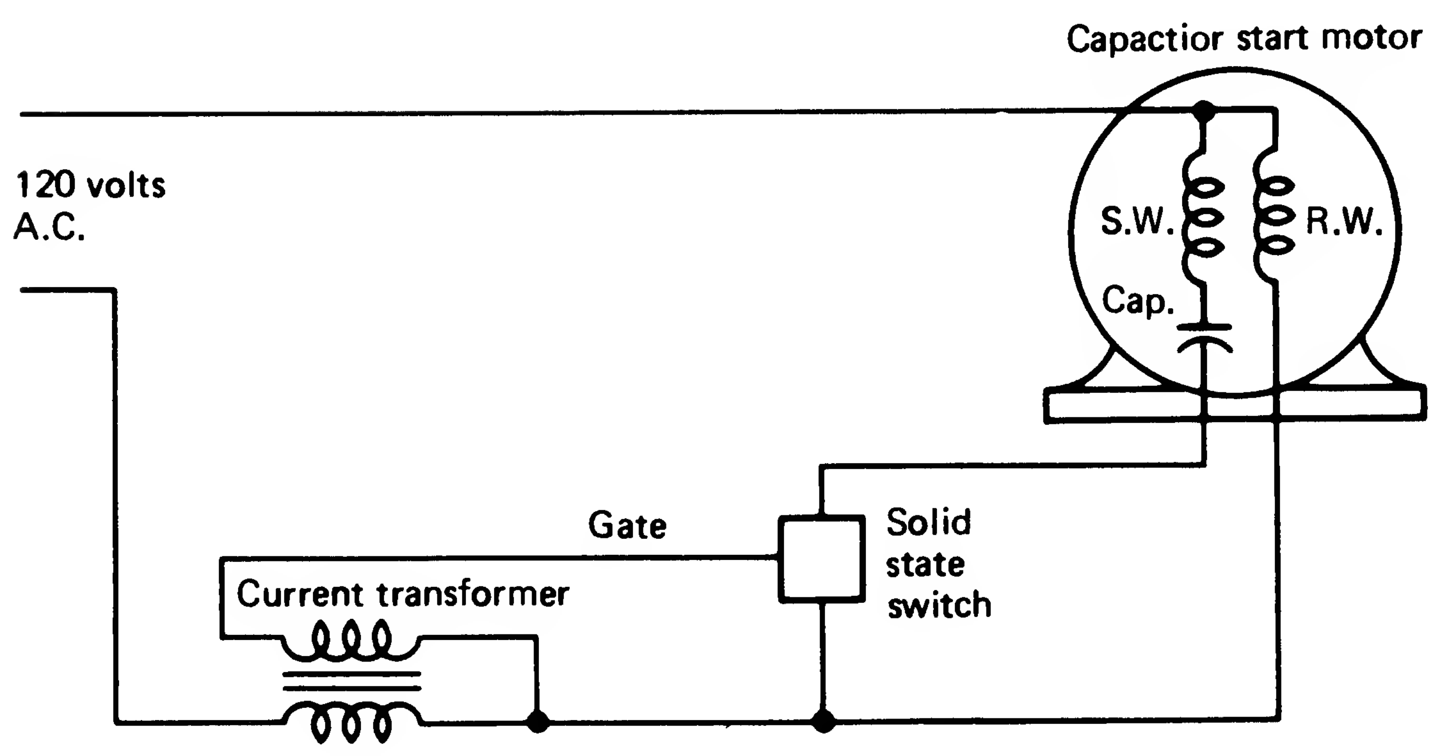


Fig. 10–79. Solid state switching of starting windings in capacitor or split-phase motors.

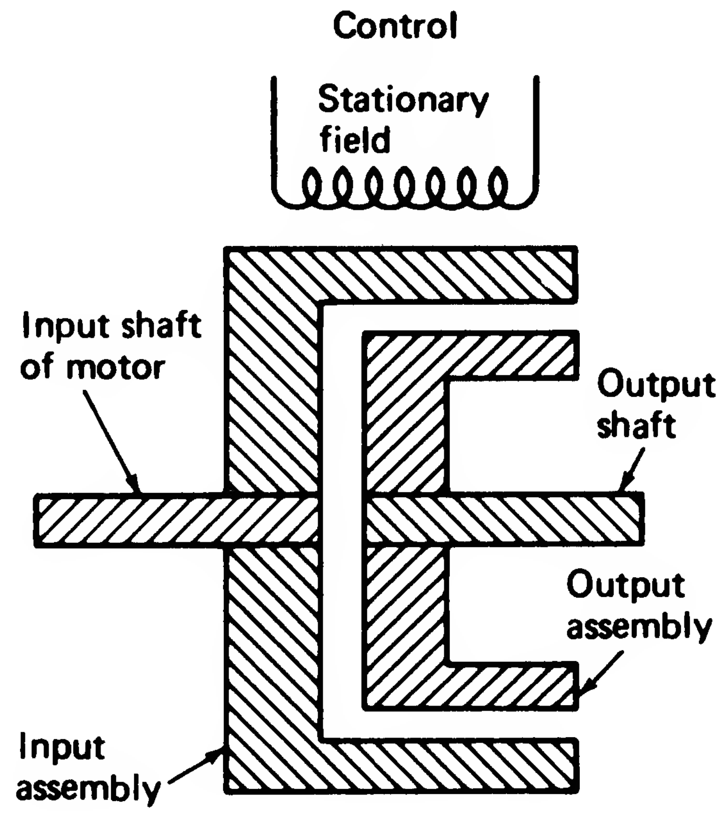


Fig. 10-80. Magnetic clutch assembly.

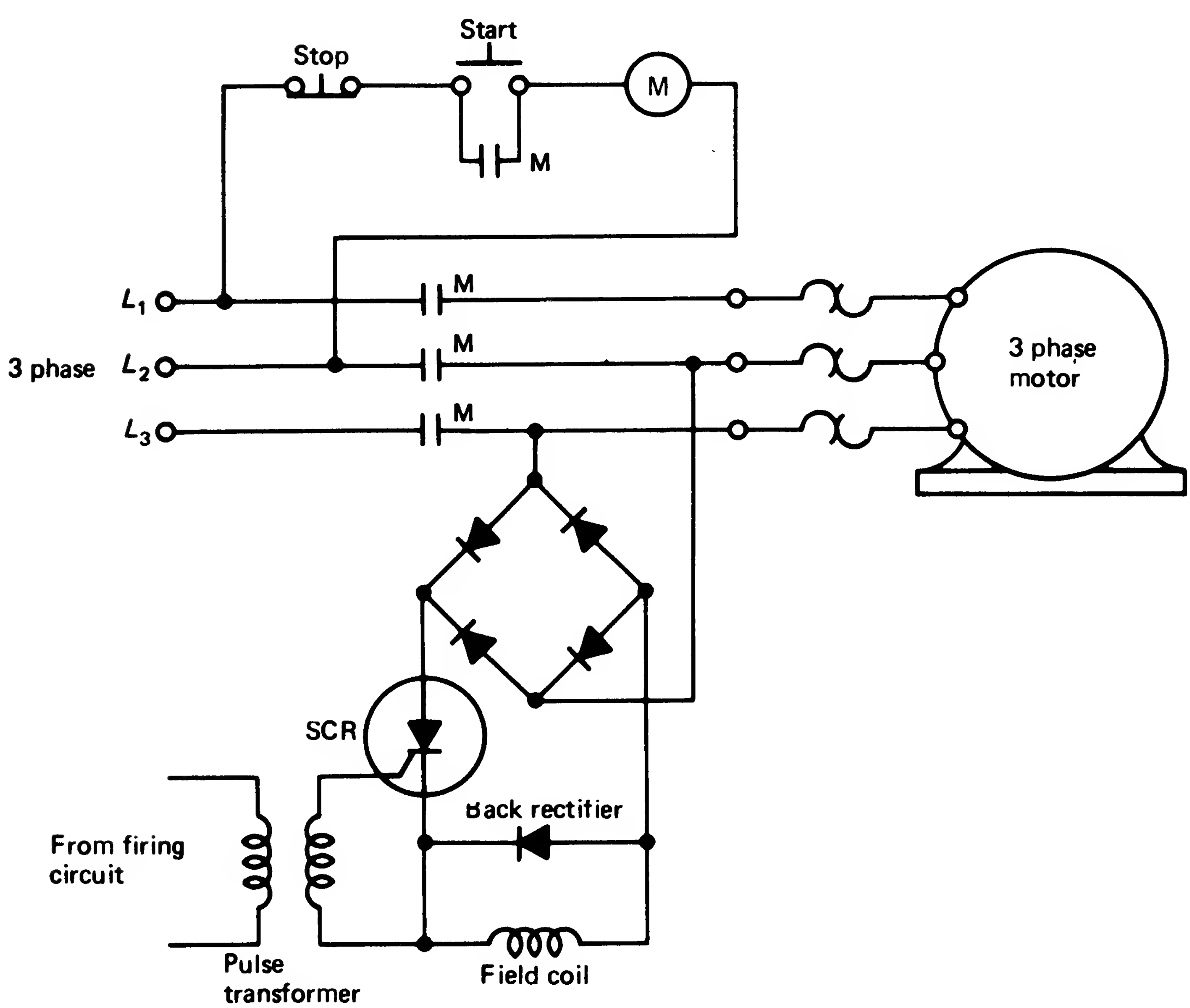


Fig. 10-81. Power circuit of a magnetic drive.

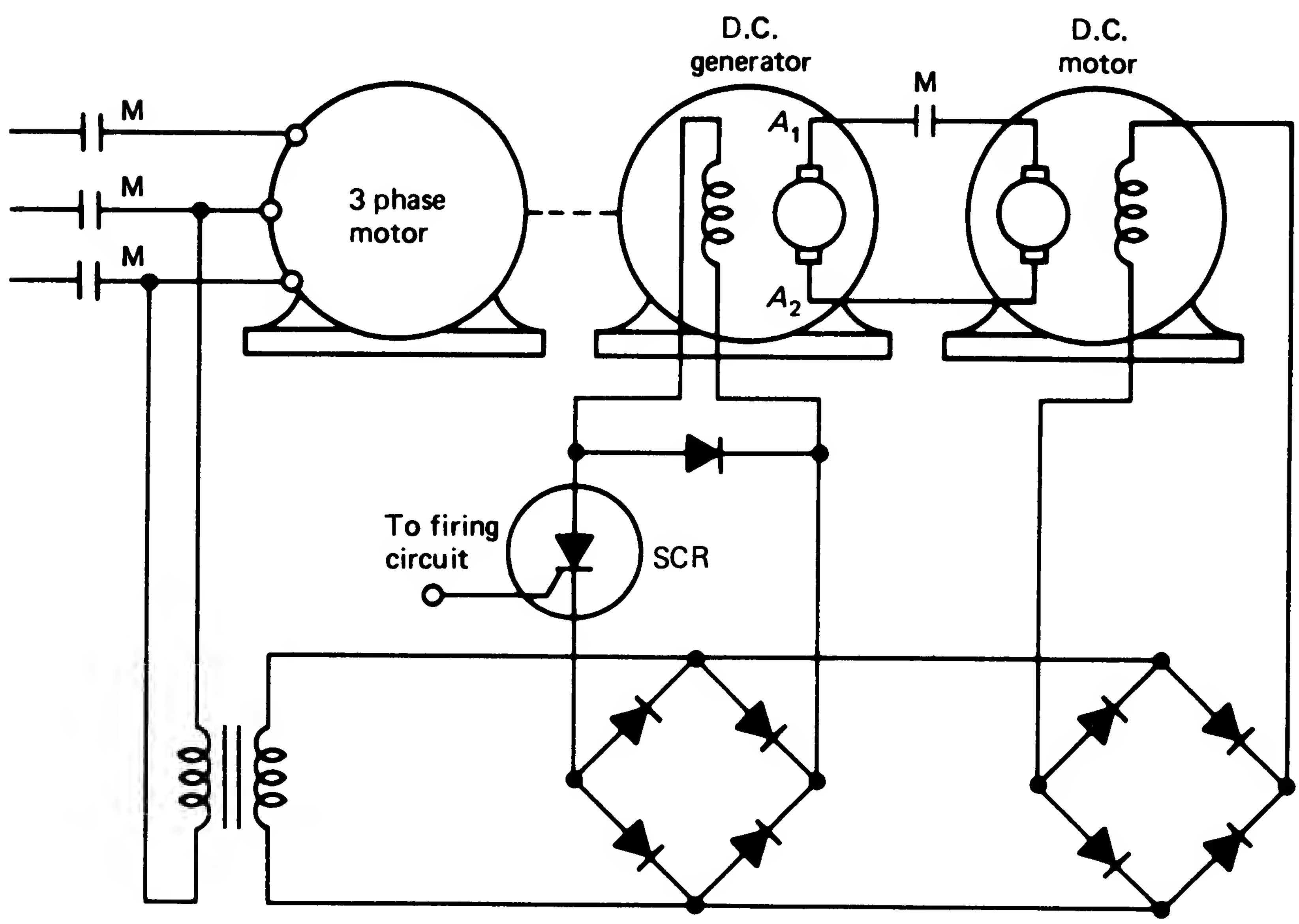


Fig. 10-82. Simplified diagram of a motor generator drive.

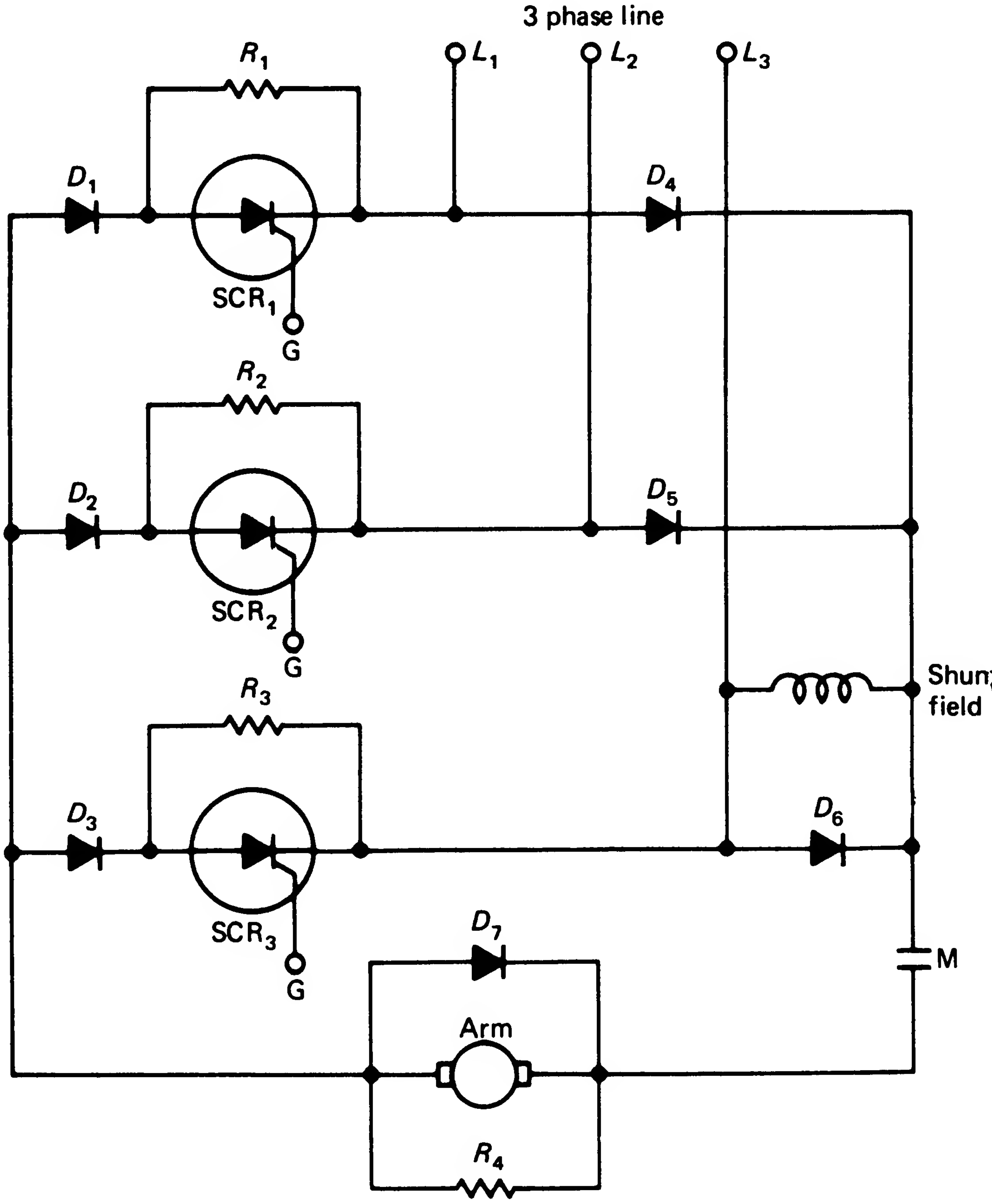


Fig. 10–83. Three-phase static drive.

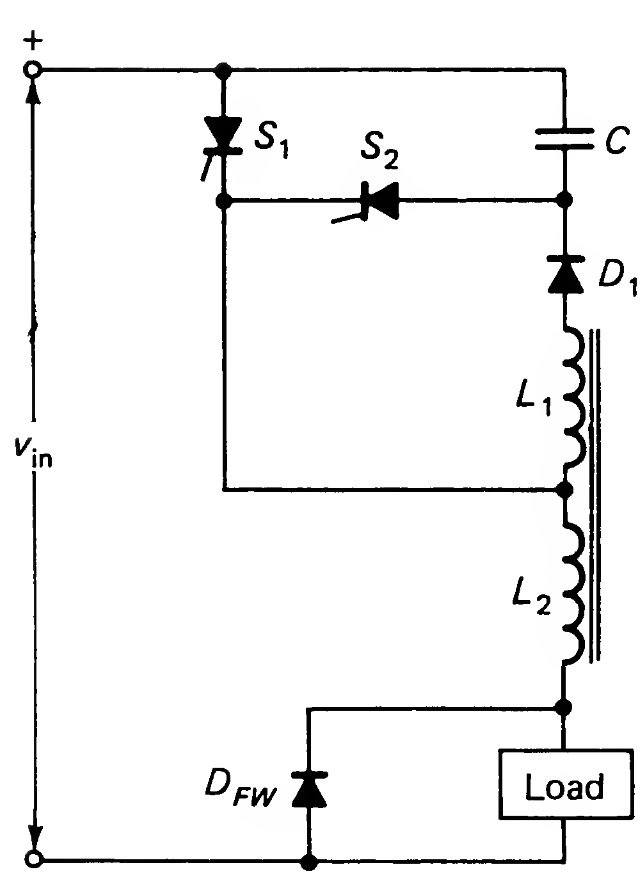


Fig. 10–84. Jones chopper controller. *(S.A. Nasar, Electromechanics and Electric Machines, John Wiley & Sons, Inc.)*

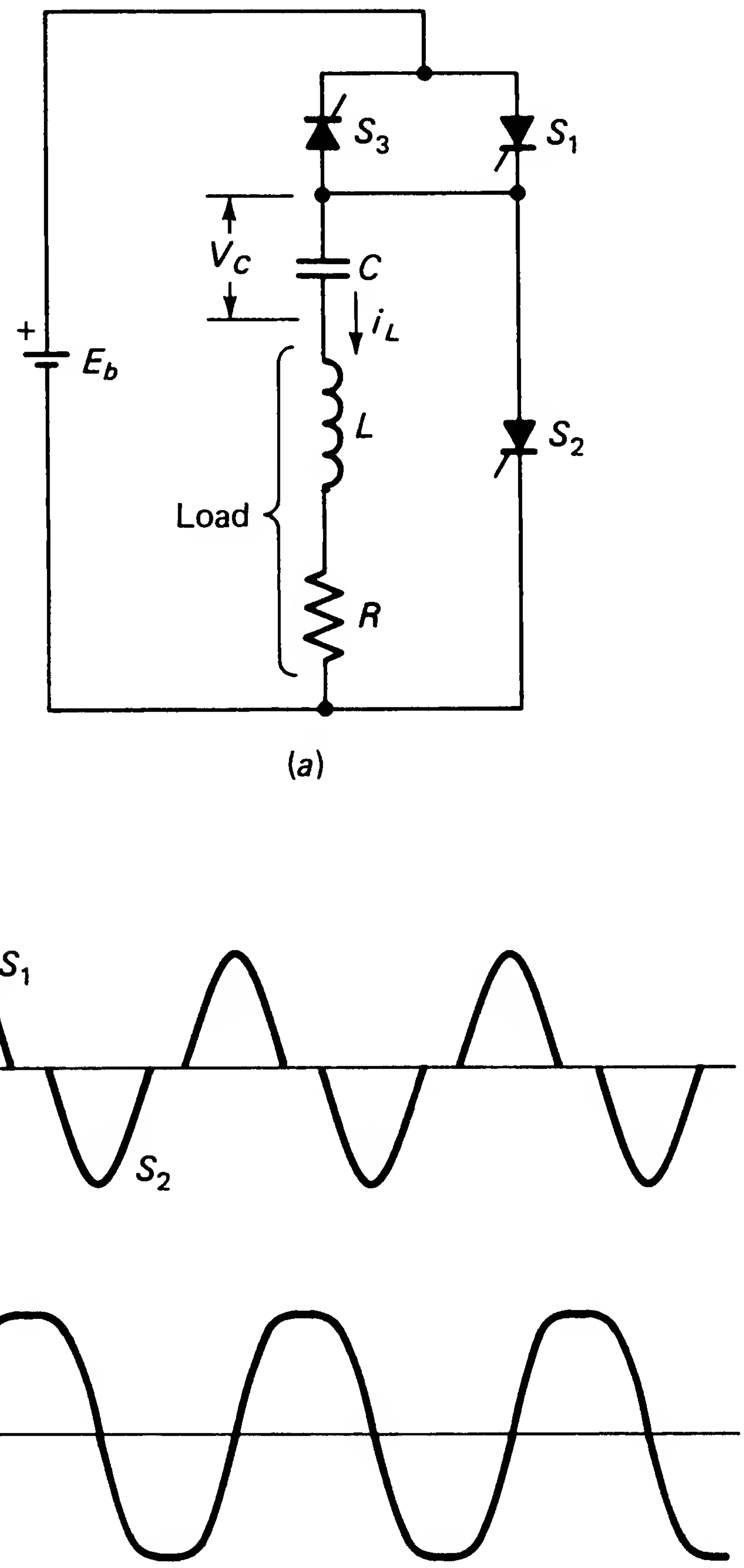


Fig. 10-85. Series inverter and waveforms. *(S.A. Nasar, Electromechanics and Electric Machines, John Wiley & Sons, Inc.)*

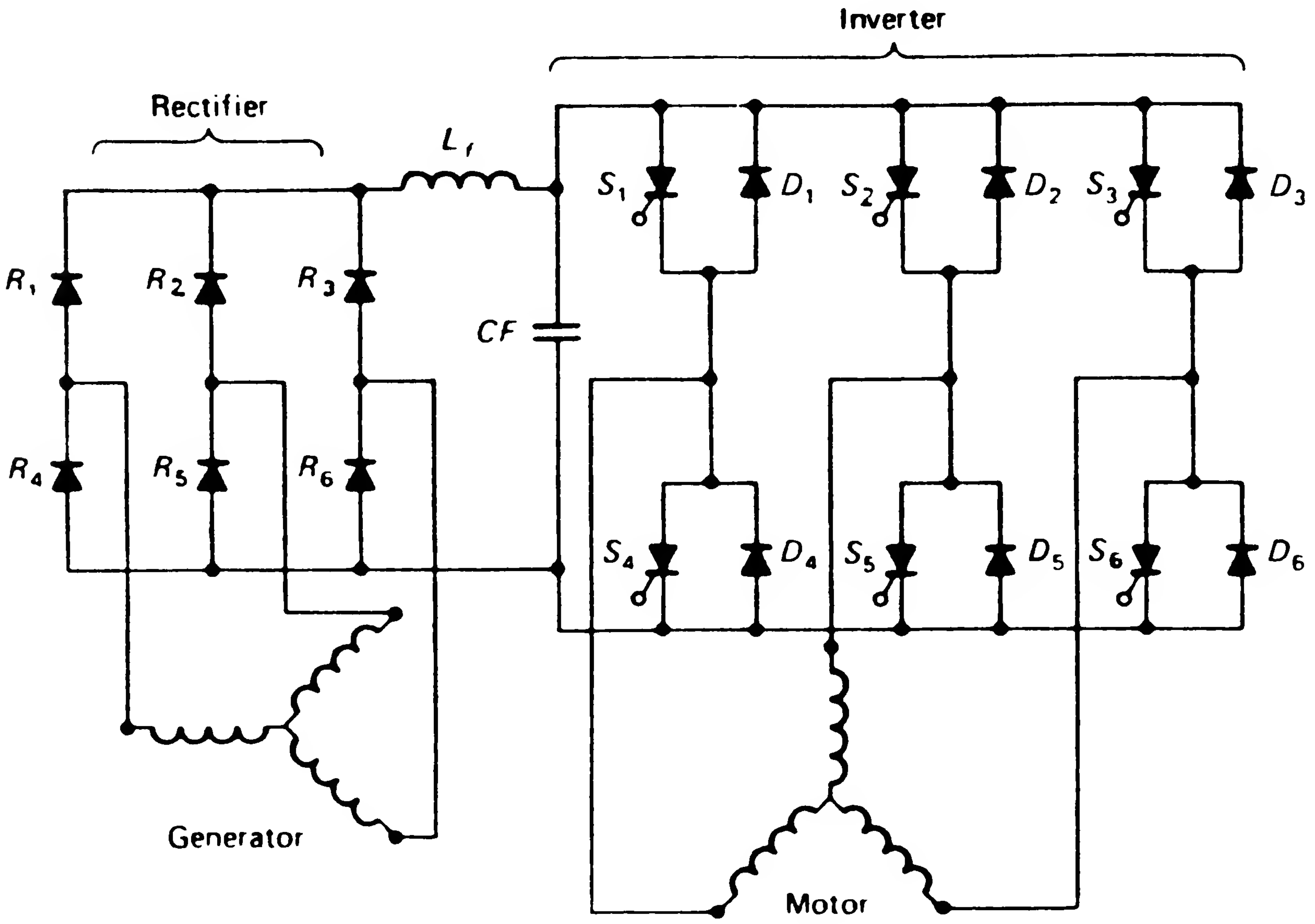


Fig. 10-86. Bridge inverter with voltage input control for three-phase ac motors. *(S.A. Nasar, Electromechanics and Electric Machines, John Wiley & Sons, Inc.)*

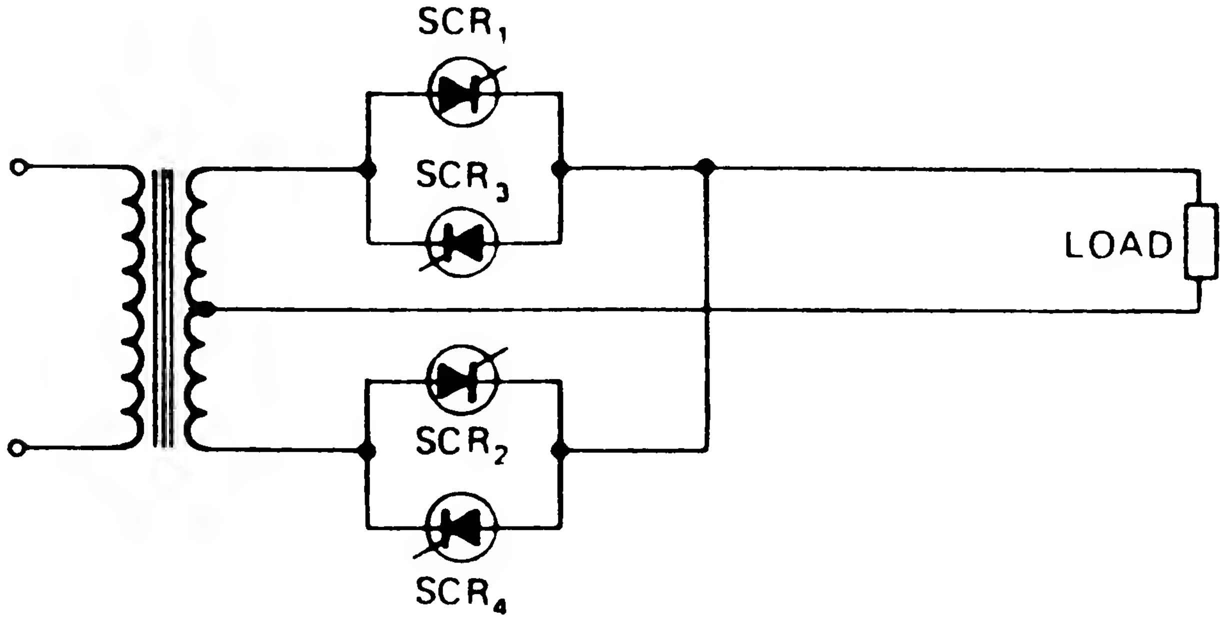


Fig. 10-87. Single-phase cycloconverter. *(General Electric Co., Semiconductor Products Dept.)*

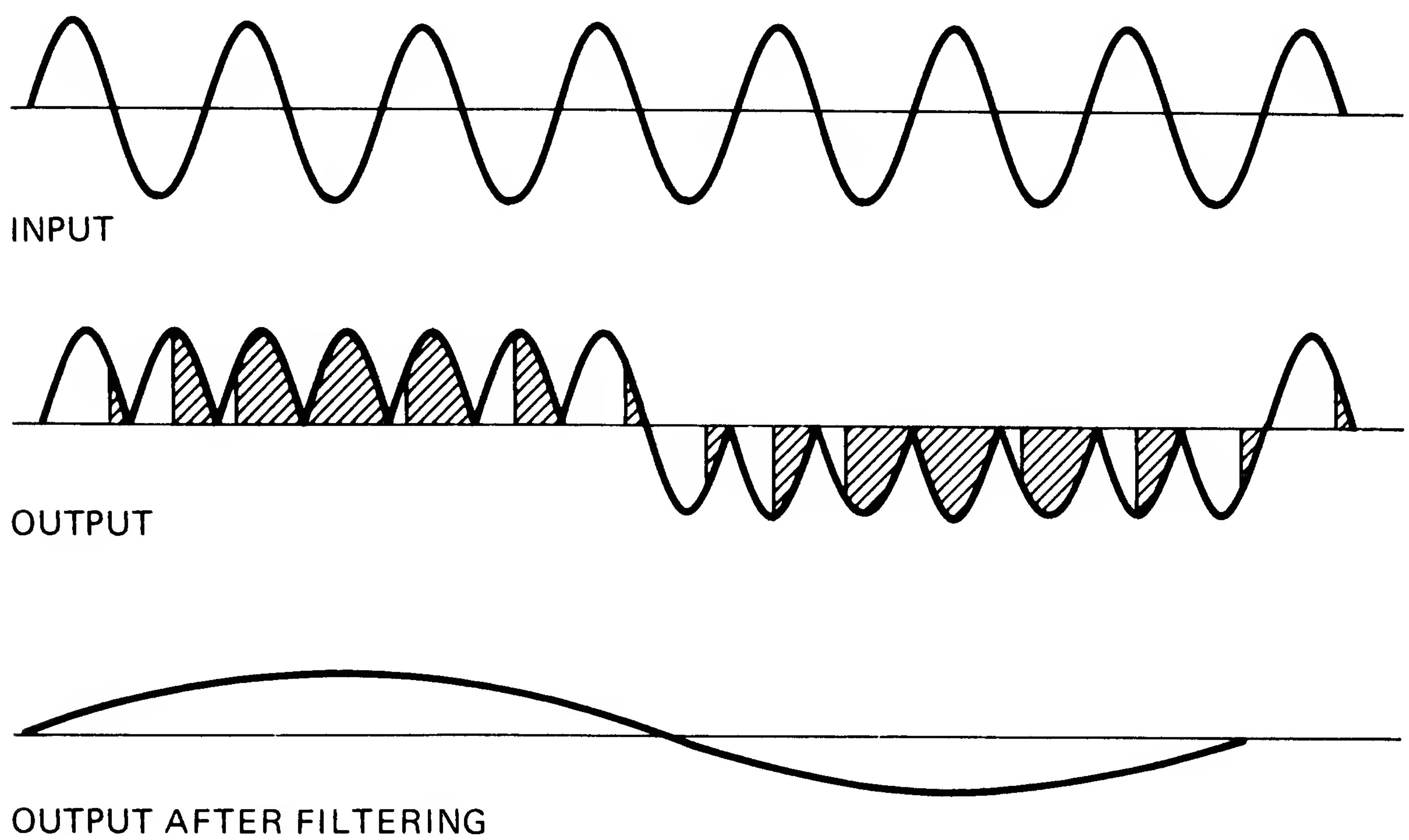


Fig. 10–88. Single-phase cycloconverter waveforms. *(General Electric Co., Semiconductor Products Dept.)*

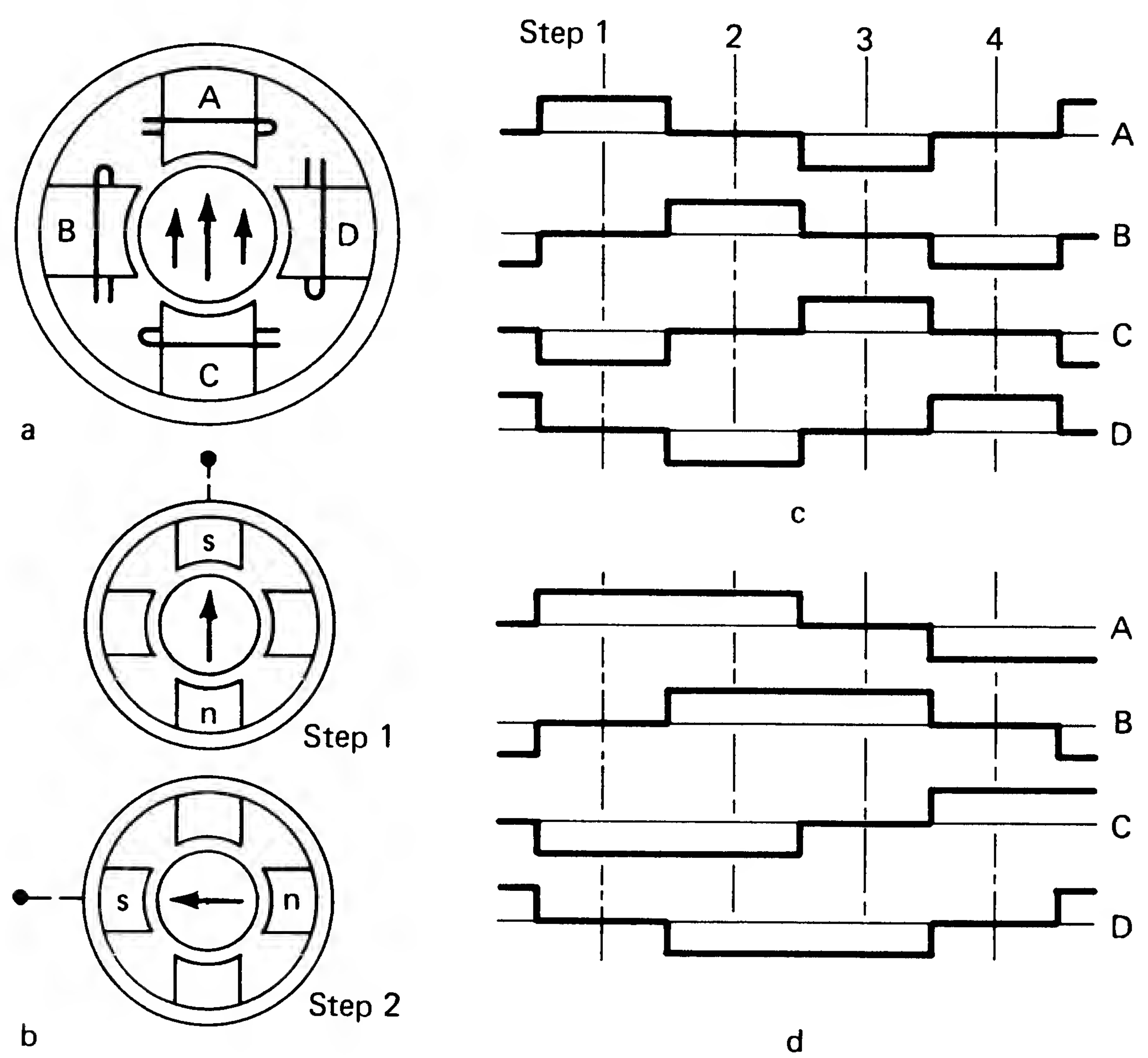


Fig. 10–89. Permanent magnet stepper motor. *(M.G. Say and E.A. Taylor, Direct Current Machines, John Wiley & Sons, Inc.)*

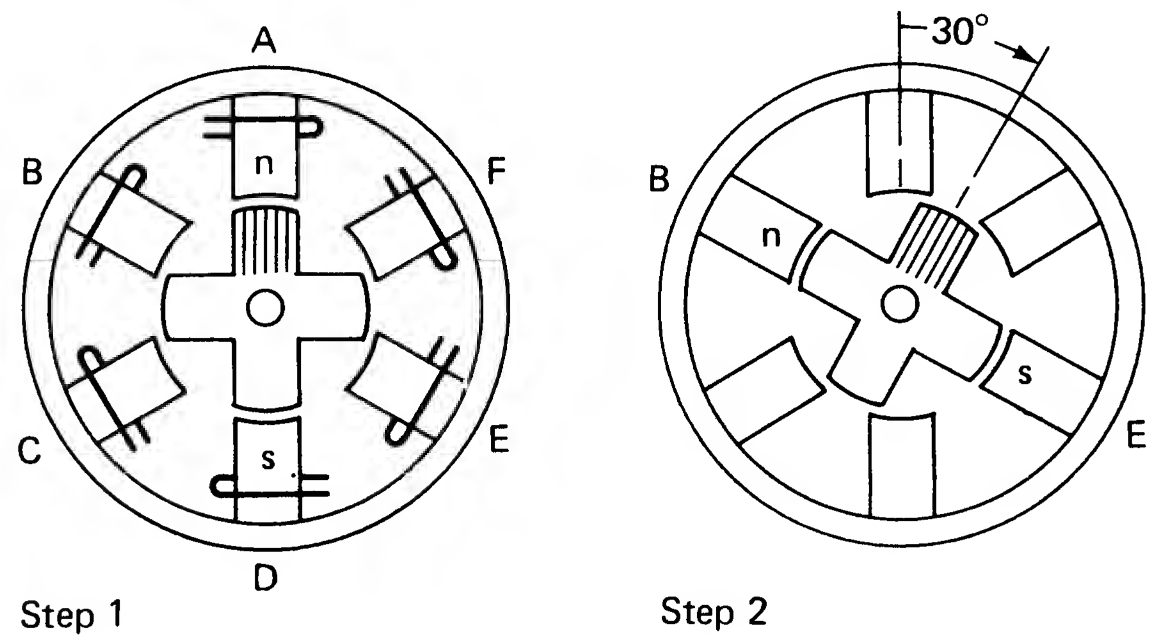


Fig. 10-90. Variable reluctance stepper motor. *(M.G. Say and E.A. Taylor, Direct Current Machines, John Wiley & Sons, Inc.)*

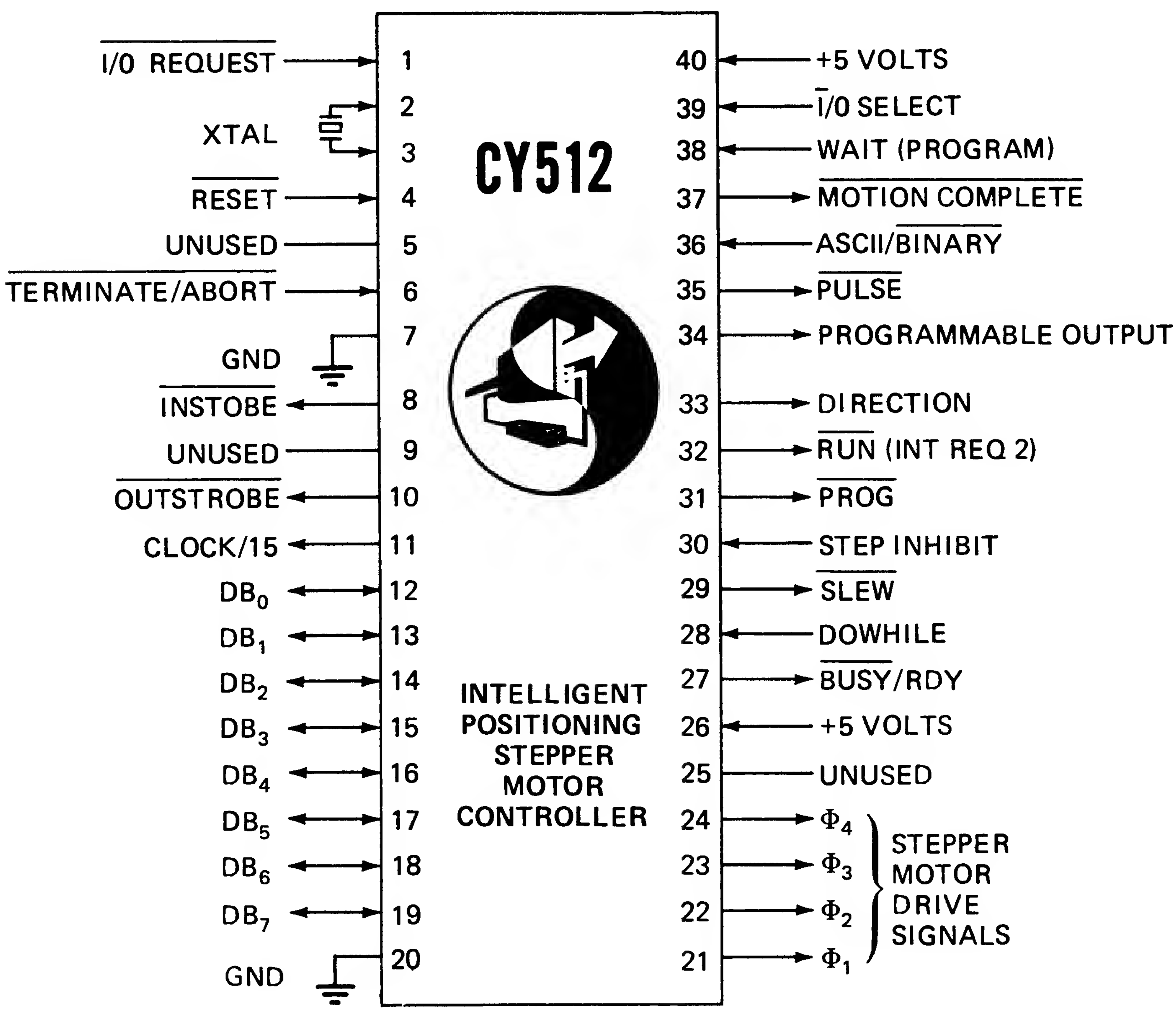


Fig. 10-91. CY512 stepper motor pinout diagram. *(Cybernetics Microsystems.)*

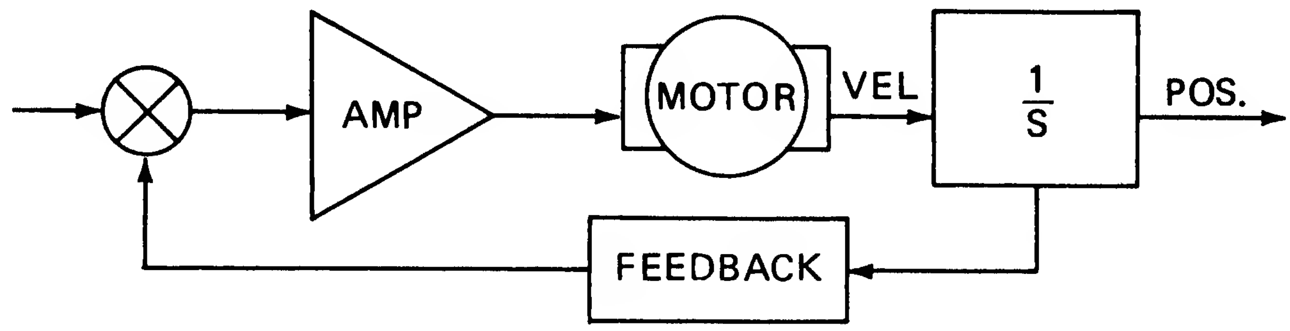


Fig. 10–92. Basic closed-loop servo system. *(J.A. Harden, "Programmable DC motor controller," Powerconversion Int., Nov./Dec., 1983.)*

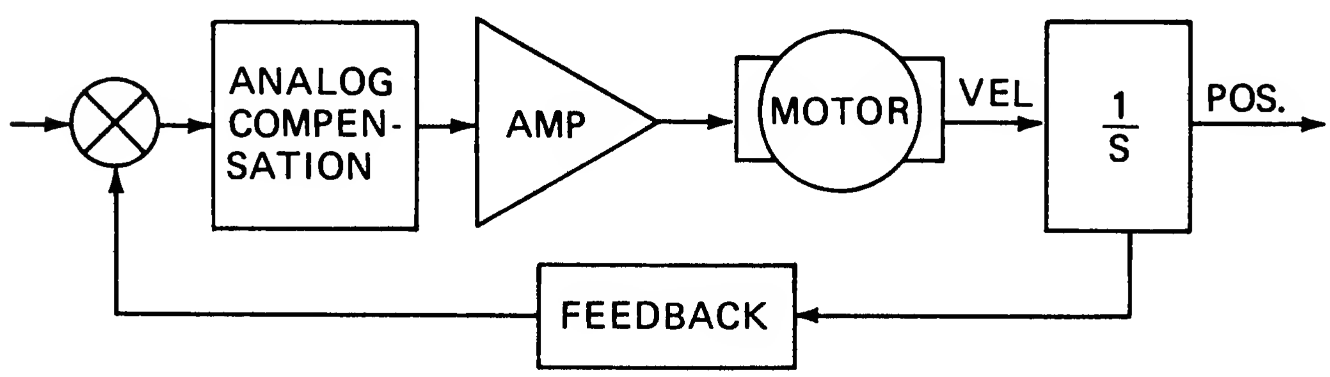


Fig. 10–93. Closed-loop servo system with analog compensation. *(J.A. Harden, "Programmable DC motor controller," Powerconversion Int., Nov./Dec., 1983.)*

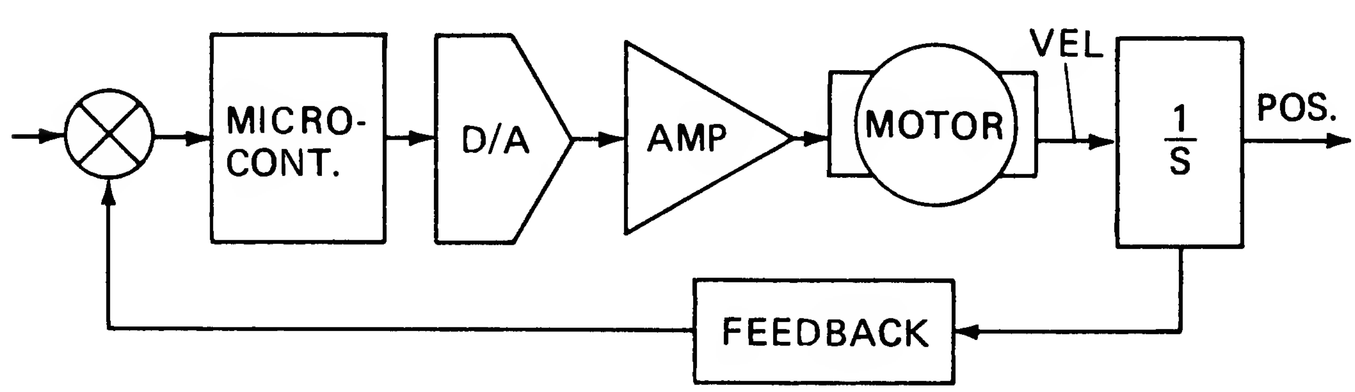


Fig. 10–94. Closed-loop servo system with digital compensation. *(J.A. Harden, "Programmable Dc motor controller," Powerconversion Int., Nov./Dec., 1983.)*

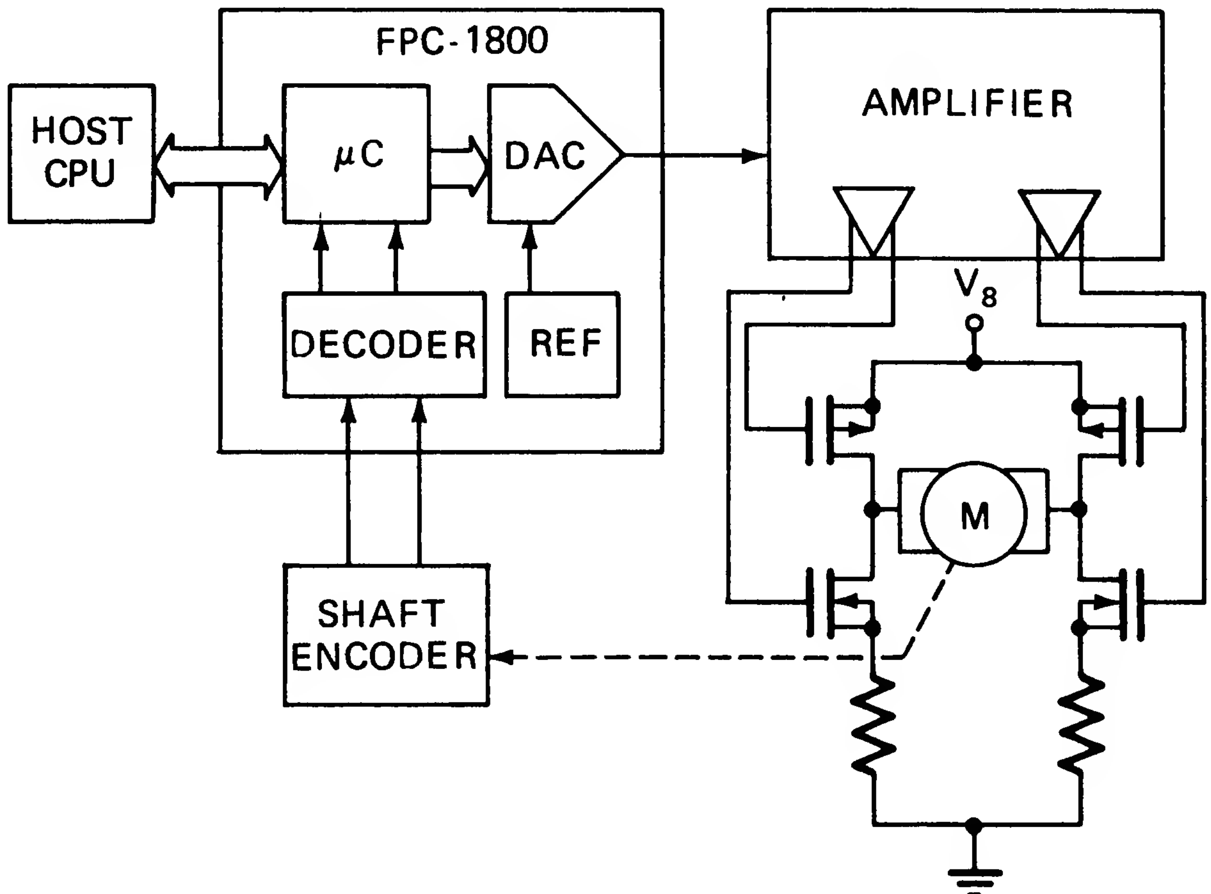


Fig. 10–95. FPC-1800 precision digital controller block diagram. *(Finnell Systems.)*